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ARTICULATORY COMPENSATION FOR A BITE BLOCK, WITH AND WITHOUT AUDITORY FEEDBACK, IN HEARING AND HEARING-IMPAIRED SPEAKERS

by

MELANIE MCNUTT CAMPBELL

A dissertation submitted to the Graduate Faculty in Speech and Hearing Sciences in partial fulfillment of the requirements for the degree of Doctor of Philosophy, The City University of New York

1999

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Abstract

ARTICULATORY COMPENSATION FOR A BITE BLOCK, WITH AND WITHOUT AUDITORY FEEDBACK, IN HEARING AND HEARING-IMPAIRED SPEAKERS

by

Melanie McNutt Campbell

Adviser: Professor Katherine S. Harris

The role of auditory feedback in articulatory compensation for a bite block was investigated. One paradigm was applied to four groups of subjects: adults with normal hearing, four-year-old children with normal hearing, adults with congenital profound hearing loss, and adults with severe hearing loss. Every subject produced 16 tokens of each of the vowels /i/, /I/, and /ae/ in a "hVt" context within a "say hVt again" carrier phrase in each of four conditions: normal, bite-block (20-mm for adults, 10-mm for children), masking (80dB), and bite-block-plus-masking. Adults with hearing loss removed their hearing aids in masking noise. F2 and F1 measurements were made for each vowel. Degree of compensation was assessed by comparing formant values in the three test conditions with those in the normal condition and with predictions from computer simulation of the effect of a bite block, if there were no compensation. Intensity and fundamental frequency measurements were also made to monitor voice source changes. Findings showed adults with normal hearing compensate substantially, but not completely, for a bite block and that auditory feedback plays a role in that compensation. Young children do not exhibit adult-like compensatory skills nor provide evidence that auditory feedback plays a role in articulatory reorganization. They may require more speech practice

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in order to use auditory feedback to guide articulatory movement. Adults with profound hearing loss over-compensate for a bite block with a more anterior placement of the tongue, but tongue height becomes more variable in a jaw-fixed condition, with or without auditory feedback, suggesting that in compensation they seek to preserve articulatory gestures specified primarily by tactile and proprioceptive information. The jaw-tongue complex exhibits movement reciprocity even though their speech targets are specified by little or no auditory information. Adults with severe hearing loss compensate like adults with normal hearing. Theoretically, the findings suggest that articulatory compensation is a speech motor skill that develops given either articulatory or acoustic targets, but the pattern of compensation for each is different. Talkers preserve articulatory gestures in fixed-jaw conditions in a manner that reflects the forms of feedback to which they had access during speech development.

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To Lorne

who gave me the courage to begin and the unfailing support to finish

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CHAPTER ONE

INTRODUCTION AND LITERATURE REVIEW

In 1932 Jesperson speculated that jaw position played no part in the production of vowels and that the shape of the mouth channel (translation from German) was all important, accomplished by the tongue quite independent of the jaw. He supported his argument with the everyday observation that some people carry on many conversations all their lives with a pipe clenched between the teeth. What Jesperson did not consider was the possibility that those speakers might be compensating for the pipe's presence.

Articulatory Compensation

During the past 30 years a number of studies have been conducted to observe the effects on speech of fixing the position of the jaw with something that functioned as an equivalent of the pipe, a bite block (Nooteboom and Slis 1970; Lindblom and Sundberg 1971a, 1971b; Lubker, McAllister, and Lindblom 1977; Folkins 1979; Gay and Turvey 1979; Lindblom, Lubker, and Gay 1979; Lubker 1979; Fowler and Turvey 1980; Folkins and Zimmermann 1981; Gay, Lindblom, and Lubker 1981; Kelso and Tuller 1983; Hoole 1987; Smith 1987; Flege, Fletcher, and Homieden 1988; Bohn et al. 1991; McFarland and Baum 1995; Baum, McFarland, and Diab 1996; Baum, Kim, and Katz 1997). The bite blocks have been made from a variety of materials including wooden doweling, plastic cubes, or wads of dental impression material fitted between the teeth on one side of the mouth. The purpose of the studies was to better understand the coordination between the tongue and the jaw for speech by creating a situation in which observations could be made of the response of the tongue to the condition of a fixed jaw.

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Many of these studies used acoustic measurements of vowel formants to make inferences about tongue movement in response to a bite block (Lindblom and Sundberg 1971a, 1971b; Gay and Turvey 1979; Lindblom, Lubker, and Gay 1979; Fowler and Turvey 1980; Gay, Lindblom, and Lubker 1981; Kelso and Tuller 1983; Hoole 1987; McFarland and Baum 1995; Baum, Kim, and Katz 1997). To know whether, and to what extent, the tongue might compensate for a fixed jaw, it was necessary to know the effect on formant values of vowels of a lowered and fixed jaw, if the rest of the vocal tract did not vary. This knowledge was obtained through computer simulation. Several investigators used articulatory models that defined procedures for deriving formant frequencies from information about parameters such as the state of the lips, position of the jaw, shape and position of the tongue, and larynx height (Lindblom and Sundberg 1971b; Lindblom, Lubker, and Gay 1979; Fowler and Turvey 1980; Gay, Lindblom, and Lubker 1981). The models related articulatory parameters to vocal tract shape and area function and then to acoustic transfer function. Jaw height could be manipulated independent of position of the tongue. Specific information about features of the articulatory models and the predictions made from them will be discussed in "Chapter Four: Computer Simulation of Bite-Block Effects on Formant Frequencies". In general that chapter states that increases in jaw opening are associated with a substantial increase in F1. If the tongue does not compensate, the inevitable consequence is that it rides along with the jaw into a lower and more posterior position, decreasing pharyngeal space and increasing F1. Changes in F2, though less extensive, are also associated with jaw opening. While the direction and the extent of the change are dependent upon the height and place of the vowel target, the lowering and the more posterior position of the tongue often lowers F2.

The knowledge that F1 and F2 would be substantially altered if the tongue did not compensate for a lowered, fixed jaw enabled investigators to compare formant measures of vowels spoken in normal and bite-block conditions (Lindblom and Sundberg 1971a, 1971b; Gay and Turvey 1979; Lindblom, Lubker, and Gay 1979; Fowler and Turvey

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1980; Gay, Lindblom, and Lubker 1981; Kelso and Tuller 1983; Hoole 1987; McFarland and Baum 1995; Baum, Kim, and Katz 1997). Most of the earlier studies measured formants at vowel onset and generally found them to be normal or near-normal in bite-block conditions, with little or no practice (Lindblom and Sundberg 1971a, 1971b; Gay and Turvey 1979; Lindblom, Lubker, and Gay 1979; Gay, Lindblom, and Lubker 1981; Kelso and Tuller 1983). Reciprocal coordination of the tongue and the jaw was observed; when the jaw could not move normally, there was greater compensatory tongue movement in order to achieve vowel targets. That acoustic evidence was validated by other types of data, too. Gay, Lindblom, and Lubker's (1981) x-ray data showing drastic articulatory reorganization for the presence of a bite block in the form of "supershapes" of the tongue and Bohn et al.'s (1991) glossometric data indicated that a bite block did not much affect the degree of precision in tongue positioning for six German vowels.

Subsequent studies, however, have questioned whether compensation for a bite block is either complete or immediate (Fowler and Turvey 1980; Flege, Fletcher, and Homiedan 1988; McFarland and Baum 1995; Baum, McFarland, and Diab 1996; Baum, Kim, and Katz 1997). Fowler and Turvey (1980) reported small, but significant, acoustic differences between normal and bite-block vowel formants. They also showed that listeners correctly identified the bite-block vowels less often. Flege, Fletcher, and Homiedan (1988) collected electropalatography data for bite-block productions of /s/ and /t/ in a carrier phrase. They reported that bite-block fricative production suffered and that the vowel /eɪ/ edited from the carrier phrase "Say to me ____ again" exhibited perceptible distortion. They suggested that more sensitive methods of study be applied to bite-block vowels.

A systematic examination of the effects of a bite block on vowels, fricatives and stop consonants was conducted acoustically by McFarland and Baum in 1995 and then perceptually by Baum, McFarland, and Diab in 1996. Both types of measures from these productions were consistent in revealing small, but significant differences between normal

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and bite-block vowels. In the acoustic study (McFarland and Baum 1995), speakers were analyzed separately and individual variability was shown, with some subjects classified as "good" and others as "imperfect" compensators.

Two of the primary motives for this study are to provide further information regarding the degree to which adults with normal hearing compensate for a bite block and to explore individual articulatory profiles of adjustments for a bite block in more detail.

The Role of Auditory Feedback in Articulatory Compensation

Investigators who measured bite-block effects on vowel formants and found the formants to be normal or near-normal largely concluded that auditory feedback plays no role in on-line articulatory compensation (Lindblom and Sundberg 1971a, 1971b; Lindblom, Lubker, and Gay 1979; Lubker 1979). It was presumed that auditory feedback is not critical to compensation because subjects were observed to produce formant values in bite-block conditions that were within the range of variability for normal vowels at the very onset of phonation, before auditory feedback could occur.

Conversely, three of the more recent bite-block studies, that showed that compensation was neither complete nor immediate, made measurements immediately following insertion of the bite block and again after 10 minutes of practice (Flege, Fletcher, and Homiedan 1988) or 15 minutes of conversation with a bite block in place (McFarland and Baum 1995; Baum, McFarland, and Diab 1996). It was found that there were changes in compensation after the practice periods, suggesting that subjects used afferent feedback, possibly auditory, to make adjustments for the bite block.

The role of auditory feedback in compensatory articulation has not been tested directly. Kelso and Tuller (1983) investigated the role of auditory and somesthetic feedback in compensation for a bite block, using 90dB white noise through headphones, in combination with temporomandibular joint and topical oral anesthetization. Of their four naive subjects, two received auditory feedback and two did not. It is unclear from their

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"Methods" section what the exact sequence of conditions was for each participant, because they limited their "discussion to normal or auditorily masked speech compared with the most extreme condition of sensory deprivation, omitting the intermediate conditions" (p.220) It is believed that none of their subjects produced speech in both normal and masking conditions. If they produced speech in a masking-plus-bite-block condition, the results, nonetheless, were unreported. Hoole (1987) directly tested the role of auditory feedback in a patient who exhibited substantial oral sensory deficits following closed head trauma and whiplash injury to the cervical cord following a sporting accident. Hoole's research design required the subject to produce speech in the following conditions: •initial unperturbed, •perturbed by white noise at 80dB delivered over headphones, •perturbed by a 22-mm bite block between the lateral incisors, •perturbed by both white noise and bite block, •final unperturbed. Of course, the white noise conditions in Hoole's paradigm resulted in an environment of both reduced auditory feedback and reduced oral sensation, given its application to this unique subject. However, an adaptation of Hoole's paradigm for speakers with normal oral sensory ability would provide a direct test of long-held assumptions about the role of auditory feedback in articulatory compensation, the central theme of this dissertation.

As already described, Hoole (1987) designed a white-noise-only condition for his research. This, too, would be necessary in the present study in order to account for any changes in voice source characteristics or formants that might be attributable to the masking noise itself. Knowing these effects would be necessary to interpretation of results from a condition where auditory masking and bite block were combined.

Lane and Tranel (1971) have described what Etienne Lombard first noted in 1911, the effects of noise on the speech production of adults. It is now widely known that a speaker changes his voice level when the ambient noise level increases and when the level at which he hears his own voice (his sidetone) decreases. Pitch changes have also been noted and may be viewed as a normal accompaniment to a change in voice level, predictable from the

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mechanics of glottal excitation in speech (Lane 1962). Increases in the duration of speech segments have been found as effects of noise, too (Ladefoged 1967; Fricke 1970). Hanley and Steer (as cited in Van Summers et al. 1988) reported that speakers reduced their rate of speaking and increased the duration and intensity of their productions in masking noise. Thus predictable changes in duration, amplitude and vocal pitch would be expected in a masking condition. Of these, monitoring amplitude and fundamental frequency changes would be prudent in a study of vowel formants because voice source changes may affect harmonics and, consequently, formant measures.

Van Summers et al. (1988) studied the effects of 80, 90 and 100dB SPL masking noise on the speech production of two male adults. They reported that a search of the literature over 40 years yielded a number of studies documenting duration, intensity and vocal pitch changes, but little other than informal observations about voice quality changes. Van Summers et al. sought to specify some of the acoustic-phonetic, including vowel-formant, changes resulting from speaking in noise. Noise had a more consistent effect on the formant data for one speaker than for the other. In the first speaker, F1 was raised in noise conditions while the range of F2 frequencies was reduced. The other subject showed little change in either formant. Beyond the obvious benefit of obtaining more information from a larger number of speakers about formant change as an effect of masking noise, the present study could also respond to a suggestion by Van Summers et al. that the effect be examined in test words within short phrases, beyond isolated words spoken in citation form used in their study. While investigation of the effects of masking noise on vowel formants would not be the primary aim here, nevertheless, documentation of the effects of a masking condition on speech production may shed additional light on the role of auditory feedback.

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Theories of Articulatory Compensation

Ultimately the results of this investigation of the role of auditory feedback in articulatory compensation will permit reflection upon the models of speech motor control. Two plausible explanations have been advanced regarding how on-line compensatory responses are accomplished. The first is a model-referenced control mechanism proposed by Lindblom, Lubker and Gay (1979) and Lubker (1979) that places the reorganization of movement at a central nervous system level. To a great extent, it is similar to a view proposed by Borden (1979) of an internal feedback mechanism. The essence of such a concept is that segments are specified as sensory referents, perhaps as spatial targets (MacNeilage, 1970) or as auditory images (Ladefoged et al. 1972). Gay, Lindblom, and Lubker (1981) have suggested that vowel targets may be represented as area-function related information, specified with respect to the acoustically most significant area-function features or points of constriction along the vocal tract. Whatever the nature of the articulatory target, it is compared against centrally-received sensory information about the context. That is, the condition of the vocal tract is "sensed". In the case of the bite-block situation, the central nervous system would sense the abnormally propped-open jaw. The central processor therefore compares the feedback about the actual context with the intended sensory consequences which yields an error signal that enables it to predict and correct errors before incorrect movements are produced. A simulation process finds a combination of movement patterns for articulators/muscles that will fit the context as determined from the centrally-received sensory information. Simulated commands generate simulated sensory consequences to arrive at a central reorganization of movement. The revised set of motor commands for reaching the target are then implemented. A model-referenced control mechanism enables the system, therefore, to simulate how near the target the collective articulators/muscles might come. It relegates lower-level neural systems to providing context information to the central processor. Evidence that speakers produce vowel

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formants in the range of normal at the onset of phonation is consistent with this speech production account.

An alternative explanation for how the system accomplishes compensatory articulation places this processing at the lower neural system level. This concept of "coordinative structures" has been developed by a number of proponents (Bernstein 1967; Greene 1972; Boylls 1975; Kelso, Southard, and Goodman 1979; Saltzman 1979; Fowler et al. 1980). The notion of the coordinative structure is derived from the literature on generativity characteristics of skilled motor performance, as in limb movements. Easton (1972) described the interactions of functionally-related reflex pathways that operate as control mechanisms for voluntary movements. The coordinative structure, a more abstract mechanism than that described by Easton, is defined as a functionally-specific set of muscles and joints constrained to act together in a cooperative fashion.

The coordinative structure explanation attributes generativity of vowel production to the organization of musculature underlying the activity rather than to any instructions those muscles may receive. Members of a coordinative structure are functionally linked and mutually determine one another's states in a systematic fashion. In turn, these organized constraints on muscles are effective by restricting what the vocal tract can do. To produce a given vowel is to parameterize the relationship among the components of the coordinative structure in a particular way.

Techniques other than the use of bite blocks have been employed to create conditions in which ongoing movements of an articulator are unexpectedly perturbed, eliciting compensatory movement by another, as when upper- and lower-lip movements for bilabial closure are altered when jaw movement is retarded (Folkins and Abbs 1975, 1976). Another technique enabled Abbs et al. (1976) and Folkins and Abbs (1977) to observe that perceptually adequate speech could be produced with a paresis of either the upper or lower lip following injection of a local anesthetic. Folkins and Zimmermann (1979) have shown compensatory upper-lip and jaw movements following an electrical stimulation producing

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involuntary lowering of the lower lip prior to bilabial closure. Brainstem pathways connecting lips and tongue with the jaw (Bratzlavsky, 1976) may be involved in processes which coordinate these articulators in bite-block and movement perturbation. Such a system is relatively continuously sensitive to sensory information and consequences of movement as it unfolds.

Investigations of movements of the limbs often use the analogy of a mass spring system (Asatryan and Fel'dman 1965; Fel'dman 1966, 1980; Polit and Bizzi 1978; Kelso and Holt 1980; Kelso et al. 1980; Fel'dman and Latash 1982). Muscle-joint linkages are viewed as dynamically similar to a mass spring with controllable equilibrium states. Mass spring systems possess the property of equifinality. That is, targets can be reached from different initial conditions and in spite of unforeseen perturbations encountered during the trajectory. It is argued that vowel production and limb movement also reach a final position under a variety of conditions, demonstrating a kind of "motor equivalence". Achievement of a given vowel target or vocal tract shape may be accomplished by specification of an equilibrium state among component muscles of a coordinative structure, as, for example, in the tongue dorsum/jaw system. This is a property of the system dynamics, not of a set of instructions it receives. As MacNeilage (1970) has stated, the constantly varying speech stream requires a production mechanism that can approach the same endpoints by a variety of routes. The coordinative structure mechanism, then, has the virtues of accounting for the production of appropriate gestures in variable and novel contexts and being able to do so without trial and error. It also has generalizability across many forms of coordinated behavior. Evidence that speakers produce vowel formants in the range of normal at the onset of phonation is also consistent with this speech production account. Baum, Kim, and Katz (1997) found substantial compensation for a bite block across nonfluent aphasics, fluent aphasics and normal control subjects. The investigators suggested that if their findings were confirmed in other studies, it might indicate "that the ability to adapt to an articulatory perturbation is mediated more peripherally than previously believed" (p. 375).

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A third, and more recent, perspective is a theory of task dynamics, or gestural theory (Saltzman and Munhall 1989). It is an extension of the coordinative structure account in that it, too, is built on the notion that a complex of articulators is marshaled for motion toward an articulatory goal and that each member of this complex can contribute to that movement. However, the goals are specified as abstract gestures, such as motion toward a constriction of the oral cavity at the lips. Once learned, as in the older child or the adult, the acoustic results of those motions are not needed to manage actively the production variability in speech (Browman and Goldstein 1990). Thus, in the mature system, feedback into on-line speech production is not modeled.

Returning to the first two theories of speech motor control, it is presumed that the model-referenced mechanism would have access to more sensory information than the adaptive, peripheral, closed-loop control of the coordinative structure, but neither is explicit regarding the types of feedback used in such ongoing movement control. Furthermore, they do not specify the sort of representation that may serve as an articulatory target. The model-referenced explanation would require a sensory referent against which to compare simulated sensory consequences. The coordinative structure concept describes the production of a given vowel as parameterizing an equation of constraint, which organizes the articulators into a single autonomous system. How that parameterizing is accomplished or what representation the equation describes is not specified, nor are the types of feedback used in on-line speech motor control or the manner in which this feedback is translated into articulatory control for compensation. Furthermore, it is not apparent that the predictions made by these theories are different at an empirical level.

The bite-block studies by Flege, Fletcher, Homiedan (1988), McFarland and Baum (1995), and Baum, McFarland, and Diab (1996), in which adjustments in compensation occurred after periods of practice or conversation with a bite block in place, as well as a parallel study by McFarland, Baum, and Chabot (1996) that found adjustments in compensation for an artificial palate after a 15-minute practice period, all suggest that

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afferent feedback is used to make error-based corrections. Important questions, then, are whether and how feedback might interact with central control instructions and/or peripheral mechanisms. As McFarland, Baum, and Chabot (1996) state, ". . . disagreements exist over the contribution of brain-stem reflex versus transcortical feedback processes in the modification of speech gestures" (p. 1093).

The need for further information regarding the role of sensory feedback in articulatory compensation is illustrated by a closer examination of the study by Gay and Turvey (1979). They investigated production of the isolated vowels /i, ɑ, u/ by two adult male speakers in conditions that manipulated four separate articulatory variables. A bite block and an artificial palate produced direct efferent interference. Anesthetization of the temporomandibular joint and oral mucosa were used to produce direct afferent interference. Three triads of each isolated vowel were produced in three conditions in the following order: bite block alone, artificial palate alone, and bite block plus artificial palate. Then either of the following condition sequences was followed with a subject:

Sequence 1	Sequence 2
•temporomandibular joint anesthesia alone	•oral mucosa anesthesia alone
•temporomandibular joint anesthesia + bite block	•oral mucosa anesthesia + bite block
•temporomandibular joint anesthesia + artificial palate	•oral mucosa anesthesia + artificial palate
•temporomandibular joint anesthesia + bite block and artificial palate	•oral mucosa anesthesia + bite block + artificial palate
•add oral mucosa anesthesia	•add temporomandibular joint anesthesia
•temporomandibular joint and oral mucosa anesthesia + bite block	•temporomandibular joint and oral mucosa anesthesia + bite block
•temporomandibular joint and oral mucosa anesthesia + artificial palate	•temporomandibular joint and oral mucosa anesthesia + artificial palate
•temporomandibular joint and oral mucosa anesthesia + bite block + artificial palate	•temporomandibular joint and oral mucosa anesthesia + bite block + artificial palate

No effects were seen for /ɑ / in any case. No effects for /i/ or /u/ were seen with anesthesia alone, artificial palate plus complete anesthesia, bite block alone, or bite block plus incomplete anesthesia. Dramatic effects on acoustic and perceptual measures were seen for

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the early tokens with bite block plus complete anesthesia as well as bite block plus artificial palate plus complete anesthesia. However, by the sixth trial, formants approached normal values.

Gay and Turvey (1979) concluded that the findings did not support a model-referenced mechanism in that anesthesia should have impaired production more than the bite block, because vital sensory information about the state of the tract necessary to simulate error correction would be absent. They reasoned that the results were in keeping with a coordinative structure mechanism, because when some members of a coordinative structure cannot vary (due to a bite block) and their states are not communicated within the system (due to anesthetization), the fulfilling of the equation of constraint controlling the mechanism is not possible (p.347). They went on to say that "the finding that afferent interference does not affect vowel production unless an efferent variable is frozen is consistent with the view that these muscles are functionally linked across efference and afference in such a way that control can be taken over by either system when the other is fixed" (p.350). After six trials, however, vowels assumed normal values. One might infer that auditory feedback enabled and was sufficient for the speech production system to eventually compensate under these extreme conditions, although it may not be normally the feedback used. Indeed, Hoole's (1987) subject with abnormal oral and pharyngeal sensitivity produced more accurate vowels with practice in a bite block condition and was presumed to rely on auditory feedback. Thus acoustic feedback may be sufficient for compensation, but may not be necessary when other feedback channels are available.

A study by Folkins and Zimmermann (1981) recorded electromyographic activity from jaw-closing muscles during speech production with and without a bite block. The hypothesis was that if a central simulation mechanism controls compensation for a bite block, it might be expected to use an efficient process that would eliminate jaw muscle activity normally used to open and close the jaw, unnecessary in the jaw-fixed condition. They found no reliable differences in EMG activity between jaw-free and jaw-fixed

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positions. This was taken as consistent with the interpretation that peripheral neuromotor processes are important in compensation. Folkins and Zimmermann concluded, however, that while lower-level neural control systems may be important in controlling articulatory interactions, central planning may also play an important role.

In summary, although three theories of articulatory compensation have been discussed here, there really are not discriminable, explicit predictions of each that are empirically verifiable. Furthermore, as Folkins and Zimmermann (1981) suggested, many different processes could operate at different levels of the motor system to coordinate the speech articulators. Nevertheless, gaining greater insight into the role of auditory feedback in that interplay would help shed light on speech motor processes in general. Thus the first theoretical question addressed in this dissertation is: To what degree do adults with normal hearing compensate for a bite block and what is the role of auditory feedback in this compensation?

Development of Articulatory Compensation Ability

The review of studies of articulatory reorganization in adult speakers illustrated that the basis for articulatory compensation ability, and the role auditory feedback may play in its accomplishment, are not completely understood. It is even less clear how or when this ability develops in the child and to what extent auditory feedback plays a role in that development. If the ability to produce speech in novel contexts is a necessary prerequisite to learning to talk, then the young child might exhibit such skills early on. In the case of the tongue/jaw complex, the close coordination of jaw and tongue might be expected to develop early to support accurate vowel production. Learning the phonology of a language might require extensive adaptation to a wide variety of postural and situational perturbations. Functional organization of the speech musculature would thus be specified quite early. On the other hand, it might be expected that differences would be seen in kinematic speech characteristics of adults and children. Experience may play a large role in

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the development of compensatory articulation. Coordination within muscle systems may result from late fine-tuning of articulatory skills necessary to achieve given acoustic or gestural targets. Thus, for children, auditory feedback in on-line articulatory compensation may play a larger role.

Several studies have employed procedures to investigate the effects of the introduction of novel speaking contexts to children. Borden (1976) and Daniloff, Bishop and Ringel (1977) conducted perceptual and spectrographic analyses of the speech of children whose oral cavities had been anesthetized in the process of dental treatment. There were differences in the extent of the effect from child to child, but slowing of speech, exaggeration of voice onset time and numerous vowel and consonant distortions were noted. Garber, Speidel, and Siegel (1980) found that five-year-old children made more speech sound substitutions and distortions with a dental appliance inserted along the maxilla than under normal speaking conditions. Smith, Sugarman, and Long (1983) investigated children's ability to speak at a faster or slower rate than normal. It was found that as early as age four, children were quite skilled in producing speaking rate changes. However, the children's faster speaking rate was associated with both an increase in peak velocity and an increase in displacement, a less efficient strategy than that of adults who change velocity and displacement variables in different relative proportions, depending on the particular speaker, to achieve faster speaking tempos (Kuehn and Moll 1976). Such evidence suggests that young children may not use adult-like strategies to compensate in novel speech contexts.

Findings from studies of bite-block effects in children have been mixed. Gibson and McPhearson (1980) investigated the effects of a bite block (creating a 10-mm interincisal distance) on the production of four long Swedish vowels in 6- and 7-year-old children. Wide-band spectrograms were made at the first glottal pulse when possible. Formant shifts were seen in vowels in the directions predicted by the model of Lindblom and Sundberg (1971a). As a group, the children appeared to be compensating, but with less than perfect

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success. While the authors report group results, a careful look at graphic displays within the study indicate some individual variation in ability to compensate, depending upon vowel. Trained listeners made narrow transcriptions of the utterances, and vowels produced in the bite-block condition were often identified as more open vowels. It was clear that the high, front vowels were not compensated completely. Perceptual data for /i/ looked worse than what would be predicted by acoustic data. Accurate perception of /i/ tokens from the normal condition (93%) fell to 47% when produced in the bite-block condition. Both the acoustic and perceptual results indicated that 6- and 7-year-olds were not compensating completely for the bite block.

Another study that also concluded from both perceptual and acoustic evidence that young children do not compensate for a bite block is an investigation by Edwards (1992). Edwards used a 10-mm-bite-block and a clenched-teeth condition with six normal-developing 3- and 4-year-olds using the vowels /i/, /I/, and /ae/ in "h__t" contexts. All of the children exhibited significant effects of jaw condition on F2 values. That is, F2 values tended to be somewhat lower in both the clenched-teeth and the bite-block conditions compared to the control condition. F1 measures were taken only in the vowel /ae/. Five of the six children exhibited significant effects of jaw condition on F1 values, which tended to be lower in both of the experimental jaw conditions. Edwards concluded that F1 was lowered because the clenched-teeth and the 10-mm bite-block conditions seemed to result in a higher than normal jaw position for /ae/. Perceptual results revealed that all /i/ tokens spoken in each condition were always identified correctly. The identification of /I/ and /ae/ tokens spoken in test conditions was significantly less accurate for the productions of two subjects. On a typicality rating scale, both /i/ and /I/ tokens from at least one test condition were rated as significantly less typical for three subjects. Tokens of /ae/ from test conditions were rated as significantly less typical for the utterances of five subjects. In agreement with Gibson and McPhearson (1980), Edwards thus concluded that young children do not compensate completely when the jaw is artificially fixed.

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A study by Oller and MacNeilage (1983) presented mixed results. One girl, 8 years of age, and one boy, 4 years, served as subjects. They produced isolated vowels /i/ and /ae/ in strings of three (V-V-V) in imitation of taped utterances of an adult model in each of three conditions: normally, with teeth clenched, and with either a 15- or 20-mm bite block. A resonance measure, called "R2" by Oller and MacNeilage, served as the dependent variable. R2 was defined as the second major resonance peak in the spectra, determined by assuming a half-power bandwidth of -3 dB. In the case of /i/, R2 was often a combination of F2, F3 and F4 since these formants were clustered and produced a very wide-band resonance in the displays. The 8-year-old produced relatively stable R2 values for /i/ which were largely and consistently lower in the clenched-teeth and bite-block condition. Furthermore, no obvious improvement was seen with practice. In contrast, the 4-year-old exhibited a lot of token-to-token variability, even in the normal condition. Nonetheless, fixed-jaw results indicated extensive adaptation. After 9 trials, R2 values in the test conditions approached those of the normal condition. The last six tokens of the 15 mm bite-block condition showed higher R2 values than the initial tokens of the normal condition. Oller and MacNeilage interpreted this as evidence that the child had made a substantial change in pronunciation strategy, resulting in over-compensation. They observed that even the later tokens of the normal condition seemed to have been affected by the strategy change, too, in that R2 rose for them as well. (Recording procedures were such that the test and normal conditions were presented in a quasi-random order.) Two trained listeners independently transcribed each vowel as one of seven possibilities (/i, ɪ, ɑ, ɛ, æ, ə, a/). Overall, listeners correctly categorized the majority of /i/ and /æ/ tokens despite the variability shown in resonance measures. The investigators speculated that the perceptual data might indicate that the children had made adjustments for the test conditions in realms other than resonance patterns, as in voice pitch or vowel duration adjustments.

Two other studies presented data that are in contrast to the conclusions drawn by Gibson and McPhearson (1980) and Edwards (1992), but are in keeping with the

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perceptual results, at least, of Oller and MacNeilage (1983). The first is Smith and McLean-Muse (1987), which examined not acoustic measures, but articulatory movement of the jaw and lips of 4/5-, 7/8- and 10/11-year-olds. Subjects produced repetitions of CVC words beginning with labial consonants (e.g. "peak", "back", "fin", etc.) embedded in the carrier phrase "He saw ___ again." There were three conditions: normal, fast-speaking, and bite-block. The bite block resulted in an interincisal distance of 8 to 9 mm. All three groups of children were shown to "quite readily compensate" (p.752) for the test conditions. Even the youngest group showed production patterns similar to that of the adults. However, Edwards (1992) pointed out that lip movements for bilabial consonants may be more ballistic in nature than those of the tongue in vowel production. Compensation within the lip/jaw complex for ballistic movements may not indicate that there is a parallel situation within the tongue/jaw complex for vowel production.

The findings of Baum and Katz (1988), too, suggested that young children are able to compensate for a bite block. Two groups of subjects, ages 4 to 5;6 years and 7 to 8;6 years, produced paired repetitions (V-V) of /i/, /u/, and /ɑ/ in imitation of a tape-recorded model. In the test condition, the children spoke with a bite block which produced a 12-mm interincisal distance. F1 and F2 measures were made using LPC analysis at the first glottal pulse and at the midpoint. Subjects were found to produce acoustically comparable vowel tokens across both conditions. It was reported that acoustic comparisons of tokens from each condition revealed that "most mean frequency differences were small, ranging from 1 Hz (F1 of /ɑ/ at midpoint for 7- and 8-year-olds) to a maximum of 68 Hz (F2 of /u/ at first glottal pulse for 7- and 8-year-olds)" (p. 1665).

These studies have reported results primarily across groups of children. While the investigators acknowledged that variability from token to token is greater in children than adults and in younger versus older children, individual patterns of compensation were not described. A notable exception was the illustration by Oller and MacNeilage (1983) of the change in direction of the 4-year-old's resonance measures for /i/ over time. Furthermore,

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careful inspection of figures and tables from each of these studies reveals interesting differences not only within one child's utterances, but between children within a group. For example, while Baum and Katz (1988) report that groups of children did not show significant differences in formant patterns between conditions, careful inspection of the table of individual child means reveals that there were six instances in which individual children in the older group exhibited mean formant values for specific vowels that differed more than 100 Hz between normal and bite-block conditions and twenty instances in the younger group. Furthermore, F2 measures for two subjects at the midpoint of the vowel /i/ differed more than 300 Hz between normal and bite-block conditions.

Gibson and McPhearson (1980) made formant measurements at the onset of the vowel. Baum and Katz (1988) and Edwards (1992) made measurements at both vowel onset and at vowel midpoint or 200 msec after onset, respectively. Baum and Katz point out that measures at the first glottal pulse differed from those at the midpoint. However, they observed that those differences occurred in both the normal and the bite-block conditions, suggesting that differences were not due to subjects' adjusting for the perturbation throughout the duration of the vowel. They concluded that auditory feedback played no role. Yet the Oller and MacNeilage (1983) profile of the 4-year-old's changes in production strategy over time might indicate otherwise. Clearly, this is an assumption that requires further testing.

In summary, further testing of articulatory compensation in young children is warranted in which careful acoustical analysis is made not only of formants, but of voice source dimensions such as fundamental frequency and amplitude, which may be used as avenues for compensation. Differences within and among children should be analyzed as carefully as group results in order to gain a better understanding of the developmental course of compensatory skills. Finally, investigation should incorporate conditions in which assumptions about use of auditory feedback for on-line speech reorganization are tested. In a child's developing system, it may be reasonable to expect that auditory

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feedback is more necessary to compensatory articulation. The adaptation of Hoole's (1987) paradigm, described above, would be useful for application to young children also. Thus the second theoretical question addressed in this dissertation is: To what degree do children with normal hearing compensate for a bite block and what is the role of auditory feedback in this compensation?

The Specification of Articulatory Compensation

The discussion now turns to a question that is distinct from asking about the role of auditory feedback in the on-line control of articulation. It is directed toward target specification in compensatory reorganization. Is an auditory representation of a vowel target critical to compensation, either as a sensory referent according to a predictive simulation account or as a representation serving to relate, link and constrain members of a coordinative structure or articulatory gesture?

It is well known that auditory feedback plays a very important role in the acquisition and maintenance of speech production. Is it also essential to the development of compensatory abilities? Do hearing-impaired speakers possess articulatory compensation skills? Are the articulators and muscles linked in a coordinative structure or marshaled in an articulatory gesture grouped only as a result of normal auditory feedback during the development of speech targets? Talkers who acquire speech motor patterns with reduced and/or distorted auditory feedback as a result of a hearing loss may have a representation for speech targets different from that of a hearing speaker. Can a hearing-impaired talker immediately reorganize articulatory movements to compensate for novel speaking situations or must there be an auditory image of the target to arrive at suitable vocal tract configurations?

If, as several have observed (Monsen 1976; Stein 1980; Stevens et al. 1983), hearing-impaired speakers use jaw displacement as a primary means to differentiate vowel targets and if they exhibit deficient tongue dorsum shaping and positioning, it may be that

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the jaw/tongue complex is not functionally linked in the same manner as in the hearing. Consequently, hearing-impaired talkers may not demonstrate immediate reciprocity in the movement of the tongue when jaw movement is restricted by a bite block. On the other hand, could the tongue/jaw complex be functionally organized, by either a predictive simulation or coordinative structure mechanism or articulatory gesture, without access to normal auditory feedback? Would articulatory compensation be demonstrated by such an organization despite the type of feedback used to establish a speech target? Fel'dman (1974) reasoned that removal of afferent information may alter dynamic properties of muscle groups without necessarily affecting achievement of the final articulatory target. Would hearing-impaired talkers reach similar final articulatory configurations in the presence of a perturbation even though they may have different or less distinctive vocal tract shapes for vowels than do individuals with normal hearing?

Three studies have addressed the question of whether speakers with hearing impairment exhibit compensatory articulation skills specific to the jaw/tongue complex. The first was Tye, Zimmermann, and Kelso (1983). This was a cinefluorographic and perceptual study of the effects of a bite block on the vowel production of three hearing-impaired speakers and three hearing subjects. The cinefluorographic results revealed that even in the normal condition, the hearing-impaired subjects exhibited tongue positions and tongue contours that were different from and more variable than those of the hearing subjects for the same vowels. For example, hearing subjects were observed to use tongue contours for /i/ and /u/ that were quite similar, yet both were distinct from the contour used for /ae/. The hearing-impaired, on the other hand, used tongue contours for /ae/ and /u/ that were quite similar, yet both were distinct from the contour used for /i/. In fact, the contour for /i/ was much more distinct for the subjects with hearing impairment than for the subjects with normal hearing. Though the hearing-impaired showed more variable tongue shaping and positioning than hearing subjects, they displayed movements that generally preserved areas of maximum constriction between the dorsum and the maxilla across jaw-fixed and

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jaw-free conditions. In the bite-block condition cross-dimension deviations a distance away from maximum constriction points were greater for the hearing-impaired, especially with respect to the portion of the tongue anterior to the region of maximum constriction. Tye, Zimmermann, and Kelso (1983) suggested that normal auditory feedback during the speech learning process may allow one to realize fewer degrees of freedom in vocal tract control. That is, hearing speakers may maintain tongue contours that are relatively constant and may adjust tongue position to distinguish among vowels, whereas hearing-impaired talkers may have learned different tongue posturing behaviors because of a lack of auditory information. Nevertheless, it was observed that increased tongue displacement was associated with increased jaw opening for the bite block in the hearing-impaired. Of the three vowels, the tongue contours for /i/ were most normal in both conditions.

Tye, Zimmermann, and Kelso (1983) were also interested in determining whether a learning effect could be observed. Because there were few tokens of each vowel in each condition, the investigators examined samples of the first word of a carrier phrase used by two of the subjects ("Eat that __.") for each token they produced. No early "searching" movements associated with error correction processes were detected.

Perceptual analysis of the productions was also performed. Eight listeners trained in phonetics transcribed the randomized vowels from both conditions spoken by two subjects. (The third had produced tokens in a "hVt" or "hVd" environment as opposed to the isolated vowels spoken by the other subjects.) The percent judged error was calculated for both speakers. There were no overall differences in judged errors as an effect of condition.

Taken together, the cinefluorographic and perceptual evidence would suggest that hearing-impaired talkers possess jaw/tongue compensatory skills as do hearing speakers. However, the data were extremely limited, because of the risks of radiation; the hearing subjects and two of the hearing-impaired talkers produced only two tokens of each vowel in each condition. The third hearing-impaired subject produced only one token of each vowel in the bite-block condition. True variability is difficult to judge from so few

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samples. Comparisons are also made more difficult in that while the same three vowels were examined for all subjects, three different carrier phrases and three different environments (CVC, CV, #V#) were used with subgroups of the subjects. Furthermore, the hearing-impaired subjects received 10-mm bite blocks, while the subjects with normal hearing received 16-mm bite blocks, yet the results from each group were directly compared.

The claim made by Tye, Zimmermann, and Kelso (1983), that an auditory representation of vowels may not be necessary for achievement of compensatory skills, is compromised by their choice of subjects. Audiological description of the subjects was brief, but it was stated that two subjects had adventitious losses, one a profound progressive loss beginning at age 12, and the other a severe-to-profound loss occurring at about 18 months of age. The third subject had a congenital loss, but of a severe-to-profound nature. She was described as having "a moderate-to-severe loss at 250 Hz and a profound loss at 500-8000 Hz" (p.103). With this choice of subjects, it is difficult to be certain that these individuals did not possess "auditory" representations of vowel targets, given their early experiences with sound, in the case of the two subjects with adventitious loss, and some residual low-frequency hearing sensitivity, in the case of the third. Despite its limitations, this evidence showed that there was some compensation by these speakers with impaired hearing.

Osberger, Netsell, and Goldgar (1986) conducted an acoustic study of articulatory reorganization in the hearing-impaired. Five profoundly hearing-impaired subjects were presented with three speaking tasks: talking normally, with a 5-mm bite block, and with a 10-mm bite block. Fourteen tokens each of six vowels (/i, ɑ, u, ae, ɪ, ɛ/) were spoken in the sentence: "Say pVp again." Three of the five subjects had postlingual hearing losses: one a childhood onset of unknown origin, another a childhood onset of genetic origin, and the last an adulthood sudden onset due to Meniere's disease. (This subject also had received a cochlear implant.) Osberger, Netsell, and Goldgar described the remaining two

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subjects as having prelingual hearing losses: one a congenital loss of unknown cause and the other a loss due to meningitis at age three. All were reported to use hearing aids consistently. Measurements of VOT, vowel duration, and F1 and F2, obtained from wide-band spectrograms, revealed significant differences only for F2, as a function of condition. F2 in the bite-block condition shifted in the direction of vowel neutralization. Further analysis by subject revealed that the postlingually deafened showed negligible differences in F2 whereas the subjects identified as prelingually deafened showed large differences in F2 in the direction of neutralizing the vowels and in terms of greater token-to-token variability. They concluded that hearing-impaired talkers were able to reorganize articulatory gestures provided that the onset of hearing loss was after speech motor control was fully developed. When onset was early, talkers "lost access to normal acoustic targets" (p.2) before speech motor control was established and therefore neutralized vowels in the bite-block condition.

While Tye, Zimmermann, and Kelso (1983) concluded that hearing-impaired talkers possess jaw/tongue compensation as do hearing talkers, the evidence from Osberger, Netsell, and Goldgar (1986) showed that some hearing-impaired talkers do and some do not exhibit articulatory reorganization, depending upon the time of onset of hearing loss. The reader will recall that Osberger, Netsell, and Goldgar placed in the prelingual loss category a subject who lost his/her hearing at age three years as a result of meningitis. Hearing children at three years of age have developed considerable speech and language skills, so an onset of hearing loss at three may have afforded this subject auditory experience. Nonetheless, it was clear that this subject and the individual with a congenital loss performed differently in this task from subjects with hearing loss of later onset.

Taken together, these two pieces of evidence suggest that age of onset of hearing loss may affect the development of compensatory articulation. This question should be tested with a larger number of subjects, carefully selected on the basis of onset and degree of hearing loss.

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One further note should be made about the Osberger, Netsell, and Goldgar (1986) study. The investigators stated that "The speech samples were obtained with and without the subjects wearing their hearing aids to determine if the auditory information which they received from their devices affected performance" (p.1). It could not be determined from the text or the figures which tokens were produced with hearing aids and which were produced without. Nonetheless, the investigators concluded that performance was similar whether or not the subjects were using their aids and that the subjects did not use auditory information available to them to effect changes. A systematic examination, again adapting Hoole's (1987) paradigm of conditions with and without auditory feedback, would allow further study, too, of on-line use of auditory feedback in compensation.

One further study provides additional information regarding compensatory skills in a subject with a congenital, profound hearing loss. Osberger, Netsell, and Johnson (1986) examined the vowel production of a 14-year-old female with no measurable hearing in either ear. The subject did not use amplification. The investigators had previously examined her ability to learn to produce the vowels /i/ and /ae/ in monosyllabic words with intensive training. An F2 by F1 plot was provided that illustrated the regions of F1 and F2 values for each of the two vowels at the onset of training. They were completely overlapped. After a "relatively long period of time" (p.2) the subject had learned how to produce the two targets as acoustically distinct vowels. In this study the investigators again presented the same vowels, /i/ and /ae/, in the identical CVC words the subject had used in previous training. There were 10 words for each of the vowels /i/ and /ae/ and they were produced five times each, yielding 50 tokens per vowel. The total 100 tokens were produced in each of three conditions: normal, with a 5-mm bite block, and with a 10-mm bite block. The whole procedure was repeated three times over three weeks, with approximately one week between sessions. F1 and F2 patterns of the tokens from each condition were analyzed. Results revealed a vowel, condition and day effect for both F1 and F2. For example, in the first week, F1 for both vowels was raised as much as 200 to

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300 Hz and F2 was lowered as much as 600 to 700 Hz in the 10-mm bite-block condition compared to the normal condition. In addition, token-to-token variability for /i/ was much greater in the bite-block condition than in the normal. By the third week, values were nearly overlapping between conditions for each vowel and variability was greatly reduced for /i/. No significant change in variability for /ae/ was seen as a function of condition or day of testing. The data showed that a profoundly deaf speaker was unable to compensate for a bite block unless given abundant practice over a significant period of time. The assumption made by the investigators was that in this speaker there was no reciprocal coordination between the jaw and tongue complex for a novel context because this talker had used jaw position as the primary means of achieving distinct vowel productions. As Osberger, Netsell, and Goldgar (1986) pointed out, this would not at all be inconsistent with the frequent acoustic finding of vowel neutralization in deaf talkers, that Monsen (1976) attributed to insufficient tongue movement.

One factor which obscures this otherwise convincing evidence is the fact that the investigators stated that this subject had participated in previous intensive training for a significant amount of time to produce /i/ and /ae/ productions distinct from each other. While the investigators did not report when that previous training took place, it must be noted that a 14-year-old who, presumably not long before, had required lengthy, intensive training with a very basic articulatory task may not have possessed well-developed speech production skills. To what extent, then, might these findings reflect not the lack of compensatory skills but the early developmental stages of vowel production?

The importance of testing for compensatory skills in subjects well-defined with respect to severity of hearing loss, age of onset, and speech production training is evident. The participation of two groups of proficient users of oral communication, one with congenital, profound hearing loss and the other with congenital, severe hearing loss, would test whether articulatory compensation is present in talkers with no auditory articulatory target specification and in talkers with reduced and distorted auditory articulatory target

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specification. In addition to F1 and F2 information, voice source measures such as fundamental frequency and amplitude, would more adequately assess adjustments made in articulatory reorganization. Thus the third theoretical question addressed in this dissertation is: Are auditory representations critical to the specification of articulatory reorganization for a bite block?

Summary of Theoretical Questions Posed and Hypotheses Tested in This Dissertation

This dissertation addresses three primary theoretical questions:

1. a) To what degree do adults with normal hearing compensate for a bite block?
1. b) What is the role of auditory feedback in this compensation?
2. a) To what degree do children with normal hearing compensate for a bite block?
2. b) What is the role of auditory feedback in this compensation?
3. Are auditory representations critical to the specification of articulatory reorganization for a bite block?

This dissertation tests the following hypotheses:

1. a) Adults with normal hearing compensate completely for a bite block.
1. b) Auditory feedback plays a role in this compensation.
2. a) Four-year-old children with normal hearing perform adult-like compensation for a bite block.
2. b) Auditory feedback plays a role in this compensation.
3. Adults with profound hearing loss compensate for a bite block, as seen in adults with normal hearing, with or without auditory feedback.
4. a) Adults with severe hearing loss compensate for a bite block, as seen in adults with normal hearing.
4. b) Auditory feedback plays a role in this compensation.

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The Organization of Chapters in This Dissertation

Chapter One gave an overview of the literature pertaining to the three primary theoretical questions central to this dissertation. By adapting Hoole's (1987) paradigm for use with four distinct populations -- hearing adults, young hearing children, profoundly hearing-impaired adults and severely hearing-impaired adults -- the three theoretical questions may be addressed.

It was crucial that the research design facilitate comparisons among individuals, groups and previous studies. Given the design requirements and the diversity of subjects participating in this investigation, special attention was essential for the selection of stimuli and bite-block size and placement. Special reviews of the literature conducted to build the rationale for the selection of stimuli are presented in Chapter Two. The review and rationale for the decisions regarding bite-block size and placement are presented in Chapter Three.

As already mentioned in Chapter One, necessary to the interpretation of any findings are computer-simulated predictions of the effect of a bite block if there were no compensation by the tongue. The prediction from computer-simulations of the effect of the selected bite block on the chosen vowel stimuli are presented in Chapter Four.

Chapter Five provides a description of methods used: subject attributes, instrumentation, stimulus lists, bite-block construction and placement procedures.

Chapter Six provides both an overview of the results chapters that follow it and the results of speech intelligibility ratings of all the adults with hearing loss, performed to describe accurately these subjects' speech skills and to offer possible explanations for the acoustic evidence from vowel formants presented in Chapters Seven, Eight, Nine, and Ten for the adults with normal hearing, the children with normal hearing, the adults with profound hearing loss and the adults with severe hearing loss, respectively. Chapter Eleven provides the results of analysis of intensity and fundamental frequency

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measurements across all four subject groups and also provides observations regarding the issue of practice effects relative to the immediacy of articulatory reorganization.

Finally, Chapter Twelve discusses the theoretical and practical implications of the findings.

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CHAPTER TWO

STIMULI: LITERATURE REVIEW AND RATIONALE

The design of this investigation, using one paradigm for four discrete subject groups - children with normal hearing, adults with normal hearing, and adults with profound or severe hearing loss - meant that an attempt should be made to select stimuli that could reasonably be used with all the groups and that could provide maximum opportunity to compare results with previous bite-block studies of each of these distinct populations. The stimuli review and selection process was especially influenced by the reasoning of Edwards (1992), who examined bite-block effects in three- and four-year-olds. Edwards used one point vowel, /i/, and two non-point vowels, /ɪ/ and /ae/. Her rationale for this selection began with her observations of the conflicting results of previous bite-block studies in children. She speculated that these differing results might have come about because of the vowels tested:

Table 2.1.--Stimuli Used in Previous Bite-Block Studies of Children

Gibson and McPhearson (1980)	Swedish vowels /ɑ:/, /i:/, /u:/, /ɯ:/produced in groups of 3 (V-V-V)
Oller and MacNeilage (1983)	/i/ and /æ/ produced in groups of 3 (V-V-V)
Smith and McLean-Muse (1987)	/i/, /ɪ/, /æ/ in "He saw CVC again."
Baum and Katz (1988)	/i/, /ɑ/, /u/ produced in groups of 2 (V-V)
Edwards (1992)	/i/, /ɪ/, /æ/ in "hVt" monosyllables

Table 2.1 shows that Baum and Katz (1988) used the point vowels /i/, /ɑ/, and /u/. They reported that children compensated for a bite block. Edwards reasoned that the point

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vowels /i/, /ɑ/, and /u/ might be easier to produce and to perceive in a bite-block condition. She cited evidence by Stevens (1972) that point vowels permit less precise articulation and further suggested that the extreme formant frequencies of these vowels may make them less apt to be confused with other vowels. Edwards did not discuss Gibson's and McPhearson's finding (1980) that older children did not compensate for a bite block during production of those same vowels, but it should be noted that the finding was based on a maximum of only three tokens per vowel. Nonetheless, the vowels /i/, /ɪ/, and /æ/ would allow comparisons among the acoustic studies by Oller and MacNeilage (1983) and Edwards (1992), the kinematic study by Smith and McLean-Muse (1987), and results for the vowel /i/ across all studies.

Table 2.2 illustrates that many bite-block studies in adults have examined Swedish vowels. Point vowels have been well-represented. /ɪ/ has rarely been used. It was reasoned that if point vowels permitted less precise articulation, as Edwards suggested, the vowels /i/, /ɪ/, and /æ/ would be appropriate stimulus choices for investigation of adult compensatory skills, too. Also, /i/ was used in all previous studies and /ae/ in three, allowing at least a considerable number of direct comparisons.

In contrast to many other studies of bite-block effects in children and adults in which stimuli were isolated vowels, Edwards (1992) embedded vowels in [hVt] contexts, realized in the words "heat", "hit" and "hat". She chose the [hVt] context to facilitate formant measurement (Peterson and Barney 1952) and to produce words that could be illustrated by pictures for use with children. For those reasons, [hVt] contexts would also be useful here. In addition, it was reasoned that the words should be placed in a carrier phrase: "Say ____ again." Use of the carrier phrase would discourage any initial /h/ or vowel lengthening that might allow speakers to make compensatory adjustments not possible during running speech. Furthermore, in producing an isolated vowel or word, a talker could delay generating a sound until he searched for appropriate tactile or proprioceptive

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sensory states. It was thought, then, that use of the carrier phrase would yield a more accurate measure of whether compensation was immediate.

Table 2.2.--Stimuli Used in Previous Bite-Block Studies of Adults

Nooteboom and Slis (1970)	Dutch vowels /ɑ:/, /e:/, /o:/, /ɛ/, /ɪ/, /i/, /ɑ/, /ɔ/, /u/ in "pVpV´pVp"
Lindblom and Sundberg (1971b)	isolated and sustained Swedish vowels /i/, /e/, /ɛ/, /æ/, /y/, /ʉ/, /ø/, /œ/, /u/, /o/, /ɑ/, /a/
Lubker, McAllister and Lindblom (1977)	Swedish vowels /i:/, /o:/, /u:/, /æ:/, /ɑ:/ in "saga mVd igen"
Gay and Turvey (1979)	isolated vowels /i/, /ɑ/, /u/
Lindblom, Lubker and Gay (1979)	isolated Swedish vowels /i/, /u/, /o/, /ɑ/
Lubker (1979)	isolated Swedish vowels /u:/, /o:/, /ɑ:/, /i:/, /e:/, /y:/, /ø/
Fowler and Turvey (1980)	isolated vowels /i/, /ɛ/, /ɑ/, /ɔ/, /ʌ/, /u/
Gay, Lindblom, and Lubker (1981)	Swedish vowels /i/, /ɑ/, /u/, /o/ produced in groups of 3 (V-V-V)
Kelso and Tuller (1983)	/i/, /ɑ/, /u/ in isolation and in "a pVp again"
McFarland and Baum (1995)	/i/, /a/, /u/ in isolation
Baum, Kim, and Katz (1997)	/i/, /u/, /ae/, /a/ in isolation and preceding the consonant /t/ [it, ut, aet, at]

There were several reasons why the vowels /i/, /ɪ/ and /ae/ were considered an ideal set of stimuli to also examine bite-block effects in the hearing impaired. Many hearing-impaired speakers presumably differentiate these vowels primarily along the dimension of vowel height. That is, they may rely heavily upon differences in jaw opening to produce these vowels (Monsen, 1976). Certainly degree of jaw opening would be a very visible cue for a hearing-impaired person's recognition of these vowels during speechreading. Therefore, artificially fixing the jaw with a bite block during their production was

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considered a good test of the presence or absence of compensatory skills in this population. Furthermore, the three known studies of compensation in hearing-impaired speakers used two, if not all three, of these vowels. See Table 2.3.

Table 2.3.--Stimuli Used in Previous Bite-Block Studies of Individuals with Hearing Loss

Tye, Zimmermann, and Kelso (1983)	/i/, /æ/, /u/ in isolation or in either "hVd" or "hVt"
Osberger, Netsell, and Goldgar (1986)	/i/, /ɑ/, /u/, /æ/, /ɪ/, and /ɛ/ in the phrase "Say pVp again"
Osberger, Netsell and Johnson (1986)	/i/ and /æ/ in isolated CVC words

For all of these reasons, the vowels /i/, /ɪ/ and /ae/ were selected as stimuli. Creation of the stimulus lists will be discussed below in "Chapter Five: Methods".

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CHAPTER THREE

BITE BLOCKS: LITERATURE REVIEW AND RATIONALE

As stated in Chapter Two, the research design here, using one paradigm for four discrete subject groups - adults with normal hearing, children with normal hearing and adults with profound or severe hearing loss - required that the selected bite-block size and placement procedure facilitate comparisons among groups in the present study and across previous bite-block studies of each of these distinct populations, while reasonably accommodating the obvious physical differences in vocal tracts between adults and young children. The sizes of bite blocks used in previous studies are summarized in Tables 3.1 and 3.2 with details of their placement. Both have varied.

Table 3.1.--Bite-Block Size and Placement in Previous Studies of Children

Previous Studies	Bite-Block Size	Bite-Block Placement
Gibson & McPhearson (1980) (6- and 7-year-old subjects)	hard rubber bite block producing IID[1] of 10 mm	between the molars
Oller & MacNeilage (1983) (one 4-year-old and one 8-year-old subject)	two white Teflon bite blocks 100 mm long, 6 mm wide, providing 15 and 20 mm width at point of tooth contact	between the teeth; groove at one end of block into which teeth fitted securely
Smith & McLean-Muse (1987) (4- and 5-year-old, 7- and 8-year-old, and 10- and 11-year-old subjects)	very firm 7-mm polyethylene cube resulting in about 11 mm IID for 4-5-year-olds	between the molars
Baum & Katz (1988) (4- and 5-year-old and 7- and 8-year-old subjects)	1.8 x 0.8 x 1.5 cm bite block constructed per Netsell (1985) but not customized; providing vertical distance of 12 mm	between the molar and premolar teeth
Edwards (1992) (3- and 4-year-old subjects)	10-mm bite block customized per Netsell (1985)	between the molars posterior to the lower canine

[1]IID = interincisal distance

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Table 3.2.--Bite-Block Size and Placement in Previous Studies of Adults

Previous Studies	Bite-Block Size	Bite-Block Placement
Nooteboom & Slis (1970)	pencil of a diameter of about 7 mm	between teeth "not too far from one corner of the mouth" (p. 56)
Lindblom & Sundberg (1971b)	"small blocks" calibrated to produce 5-, 15-, 25-mm openings (p. 16)	"between their teeth" (p. 16)
Lubker, McAllister & Lindblom (1977)	a small bite block producing 10 mm IID and a large bite block producing 20 mm IID	between the molars
Lindblom, Lubker & Gay (1979)	small wooden blocks 3 mm wide, 3 mm deep, and grooved at each end, providing IID of 2.5 mm for open vowels and 22.5 mm for close vowels	a few millimeters away from the midsaggital plane between subject's lateral incisors
Lubker (1979)	a hard rubber block providing IID of 20 to 23 mm	between the molars
Fowler & Turvey (1980)	wooden doweling 14 mm in height and 10 mm in diameter	between the front teeth
Gay, Lindblom, & Lubker (1981)	22.5-mm and 2.5-mm bite blocks for close and open vowels, respectively	between central incisors, somewhat laterally so as not to obstruct midsagitally
Kelso & Tuller (1983)	small acrylic cylinders of 5 mm for open vowels and 17 mm or 23 mm (depending on subject's oral dimensions) for close vowels	wedges carved at each end to fit snugly "between the teeth" (p. 219)
Tye, Zimmermann, & Kelso (1983)	bite blocks molded from dental acrylic of 8, 10 and 16 mm	between the incisors
Osberger, Netsell, & Goldgar (1986)	5-mm and 10-mm bite blocks per Netsell (1985)	between the molars; posterior to lower canine
McFarland and Baum (1995)	three bite blocks of dental Express putty adjusted for each speaker, ensuring IIDs of both 22.5 mm and 2.5 mm for all vowels and 10 mm for conversation practice and postconversation testing	not stated

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Baum, Kim, and Katz (1997)	two bite blocks of dental impression material of dimensions 25x15x7.5 mm and 5x15x7.5 mm made for each subject and adjusted to ensure vertical distance between first premolars of 22.5 mm and 2.5 mm	between first premolars on left side

Given the great variation in size of bite blocks used in previous studies, it was difficult to decide upon the scale of bite blocks for adult versus four-year-old subjects. If change in jaw size were linearly proportional to change in the dimension of the chewing or speaking stroke, one might have arrived more easily at an appropriate scaling procedure. However, these relationships have not been investigated directly and would have constituted a separate study in their own right. Nonetheless, information from three sources was brought to bear upon an attempt to make a rational decision about what scaling to use.

Though this author knows of no studies of jaw motion in children for chewing or speech, Gibbs and Messerman (1972) provided some pertinent information about the dimensions of this movement in adults. They used a specially-designed instrument, the Case Gnathic Replicator, which allowed the accurate digital recording of the motion of the entire jaw. It consisted of two face bows attached to the teeth by cast-formed clutches, cemented to the labial surfaces of the teeth. They were reported not to interfere with articulation or mouth-closing. Digital transducers mounted between the face bows measured the jaw motion with respect to the skull. Jaw movements during speech (reading aloud) and chewing were observed.

Gibbs and Messerman (1972) reported data from two adult subjects with ideal occlusion. The data were presented primarily in the form of ratios. Observations of the central incisors, in both the frontal and sagittal plane, revealed that there was two-to-four-times more vertical opening for chewing than speech. While the condyles moved vertically

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during chewing, there was very little vertical condylar motion during speech (0.05 inch for one subject; 0.1 inch for the other). Movements in the horizontal plane were also recorded. Less than a 0.1-inch range of lateral movement appeared in speech movements whereas lateral movements of 0.7 inch for chewing were observed. Nonetheless, the ratio of horizontal to vertical movements was greater for speech (approximately 1:3) than for chewing (approximately 1:7).

While the text did not provide information about the actual distance of the vertical jaw excursion, one could, by using a ruler and the scales of measure provided in Figures 2, 3 and 4 of Gibbs and Messerman (1972), roughly determine the range of jaw motion in the vertical plane. The following distances were estimated from those figures. The stars indicate instances where information was not available.

Table 3.3.--Estimates of Vertical Jaw Excursion from Figures in Gibbs and Messerman (1972)

	Subject 1		Subject 2	
	Speech	Chewing	Speech	Chewing
Vertical Plane Movement Fig. 2	.5 in	1.4 in	.56 in	1 in
Sagittal Plane Movement Fig. 3	.48 in	1.34 in	.53 in	1.09 in
Typical Vertical Area of Jaw Motion Fig. 4	*	*	.34 in	.95 in
Typical Sagittal Area of Jaw Motion Fig. 4	*	*	.34 in	.95 in

It was difficult to arrive at "normalized" values given this limited information, but the values in Table 3.4 were taken as reasonable estimates.

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Table 3.4.--Estimated Distances of Vertical Excursion for Speech and Chewing from Figures in Gibbs and Messerman (1972)

Mean of Vertical Excursion for Speech (mean of values from Figures 2 and 3 for two subjects)	.51 in or 12.75 mm
Mean of Vertical Excursion for Chewing (mean of values from Figures 2 and 3 for two subjects)	1.2 in or 30 mm

A bit more information was gleaned from Figures 7 and 10 of Gibbs and Messerman (1972) relative to the observed vertical motion for specific vowels. While data were provided for six subjects pronouncing four different monosyllables, the two figures of most interest were Figures 7 and 9, where movement was illustrated for the syllables "reef" and "wan". Again, using a ruler and the scales of measure provided in the figures, an average vertical excursion for "reef" was estimated at .4 inches or 12 mm. It was presumed that the syllable "wan" was pronounced as [wɑn], though phonetic information was not provided. While the vowel of interest in this study is the front, open vowel /ae/, information about a back, open vowel provided at least some insights about jaw excursion for open vowels. An average vertical jaw excursion of .65 inches or 16 mm was estimated for the syllable "wan." Table 3.5 summarizes the estimates of vertical excursion.

Table 3.5.--Estimates of Vertical Excursion for Vowels, Speech and Chewing from Figures in Gibbs and Messerman (1972)

Monosyllable "reef"	Monosyllable "wan"	Speech (oral reading)	Chewing
12 mm	16 mm	12.75 mm	30 mm

It appeared, then, that the selection of a bite-block size of 20 mm (that is, a bite-block size resulting in an interincisal distance of 20 mm) would open the jaw beyond a typical vertical opening range observed for close vowels, open vowels, and running speech, yet not beyond a range observed in normal chewing. It should be noted that Tye,

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Zimmermann, and Kelso (1983) found that an 8-mm jaw displacement did not increase tongue movement over the normal condition. Conversely, one male adult subject in the study by Lindblom, Lubker, and Gay (1979) was unable after many trials to compensate for a 22.5-mm bite block. The investigators concluded that this size of block may have taken the jaw/tongue complex out of the range of complementarity. A 20-mm bite block also fell within the range of bite-block sizes used in previous studies.

Gibbs and Messerman (1972) did not provide information about the actual jaw sizes of the adult subjects in whom they observed these dimensions of movement. However, some insights were drawn from another source.

Broadbent et al.'s Bolton Standard of Dentofacial Developmental Growth (1975) represents a large longitudinal study of craniofacial development. During the 1950's approximately 5000 children were radiographically recorded on a longitudinal basis, every 6 months for the first four years of life and thereafter on an annual basis to young adulthood. These records resulted in the creation of what are called the "Bolton Faces" or the "Bolton Standards." These standards are not purely statistical means drawn from the population, but they are related to general concepts of normality including statistical, anatomical, functional and aesthetic normality. (The primary motivation for the study was to produce standards for the field of orthodontia.)

Thousands of x-rays were studied for a careful morphological comparison. It was noted that concentration upon the relation of the maxilla to the mandible obscured the significance of the total cranial base. Certain basic skeletal components were seen to influence the spatial position of dentition and from this foundation a set of craniofacial measures were developed. Observing the distribution of these measures in individuals at each age led to the ability to screen the population for "optimum" cases in which there was optimal facial and developmental growth. Sixteen male and sixteen female faces were selected as most representative. The tracings from those faces were averaged at each chronological age to form a single composite "optimum" face at one-year intervals. Dr. B.

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Holly Broadbent, Director of the Bolton-Brush Growth Study Center, gave permission for one figure and two standard transparencies from the Bolton Standard of Dentofacial Developmental Growth to be reproduced here. They include an overview of changes with chronological age as well as the "optimum" faces for age 4 and age 18, sagittal views.

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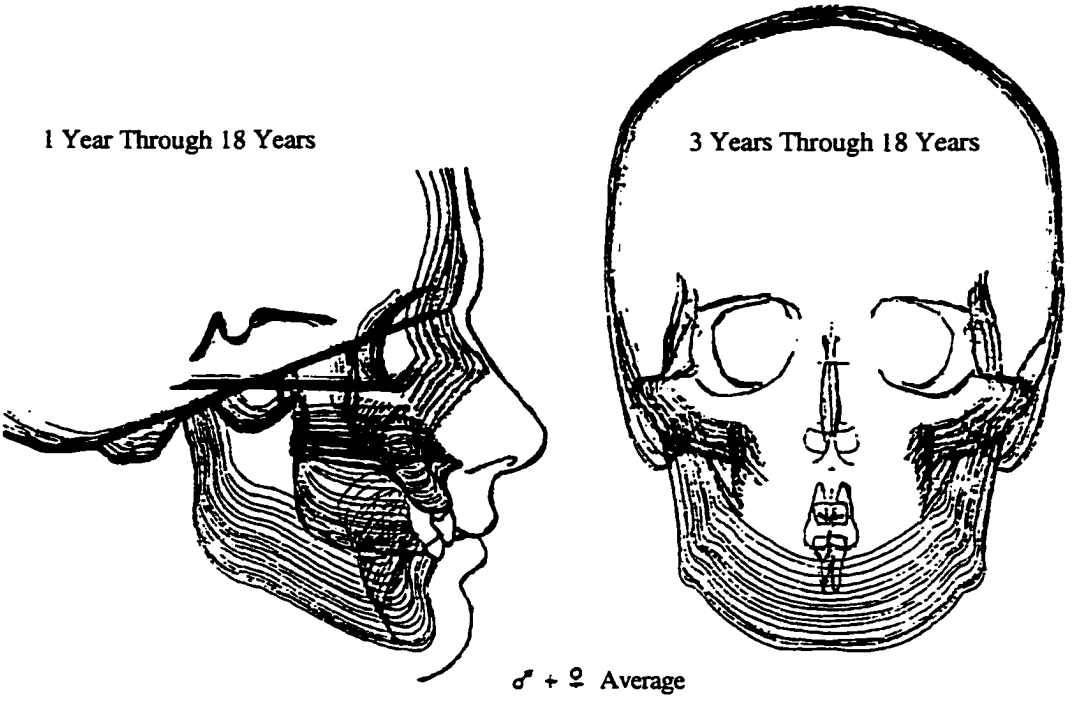


Fig. 3.1. Dentofacial Annual Growth Charts From the Bolton Standards
Lateral and frontal views reprinted with permission of B. Holly Broadbent from "Fig.4-4. Annual Bolton Standards. Both lateral and frontal views superimposed in Bolton relation.", p. 67 of Broadbent, Broadbent, & Golden, (1975), Bolton Standards of Dentofacial Developmental Growth.

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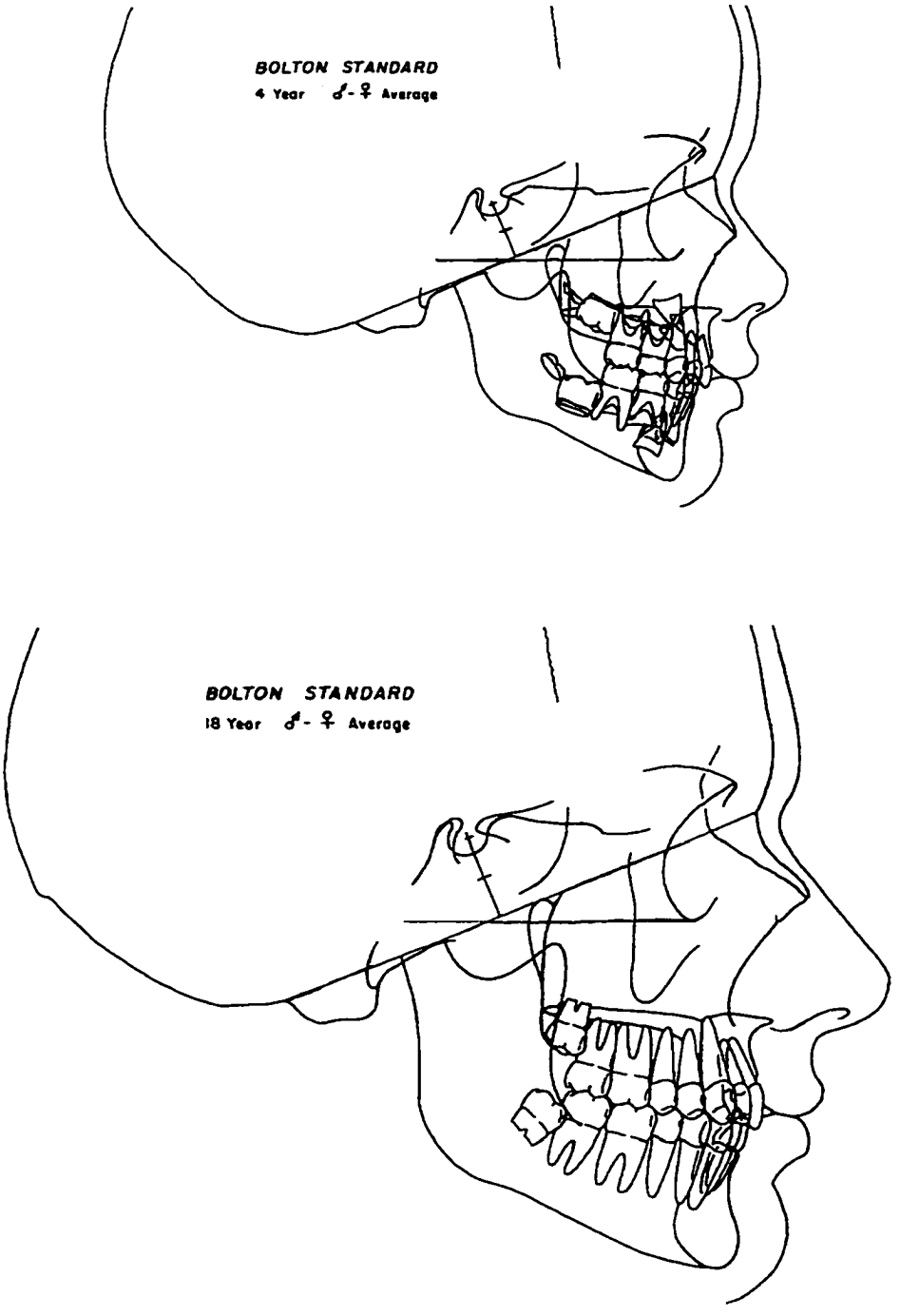


Fig. 3.2. The Bolton Standards for Four and Eighteen Years of Age
Reprinted with permission of B. Holly Broadbent from standard transparencies of lateral views from the "Bolton Standard 4 Year ♂♀ Average" and the "Bolton Standard 18 Year ♂♀ Average" in Broadbent, Broadbent, and Golden, (1975), Bolton Standards of Dentofacial Developmental Growth.

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Tracings of male and female faces were resolved into one standard. Morphological patterns were reported to be the same except for a dichotomy of size, most apparent between ages 12 and 15 years. Nevertheless, there was, in fact, tremendous overlap between the measures for each sex. Areas that were larger in males were primarily the sinuses, the nose, the mandibular symphysis and the external mandibular angle, none of which contributed significantly to orodental relationships.

The Bolton Standards covered ages 1 to 18 years. It was assumed that the tracing for the 18-year-old was representative of the adult subjects in this study. Two measures, of the many available from the Bolton study, were selected to explore the relation between jaw size and the dimension of the chewing or speaking stroke (See Figures 3.3 and 3.4.). Linear measure #2c and angular measure #5 were considered. Measure #2c was of the distance from the anterior nasal spine (ANS) to the menton (Me) of the mandible, perpendicular to the horizontal plane. In 18-year-olds the mean distance, male and female subjects pooled, was 65.4 mm. Measure #2C in 4-year-olds yielded a mean of 48.1 mm. It is clear from the measures and from the earlier illustrations that there is considerable growth of the jaw in the vertical dimension from age 4 to age 18 years.

Would this mean that the speaking/chewing stroke also changes as the jaw grows? It may not. Looking at the Bolton angular measure #5 (the angular relation between a line drawn from the lower rim of the orbit of the eye (Or) to the porion (Po) of the skull and a line drawn from the sella turcica (S) of the skull to the gnathion (Gn) of the mandible), there was little change between age 4 (57.9 degrees) and age 18 years (60.2 degrees). Though the absolute size of the structures changes, the range of the motion of one structure relative to another may not.

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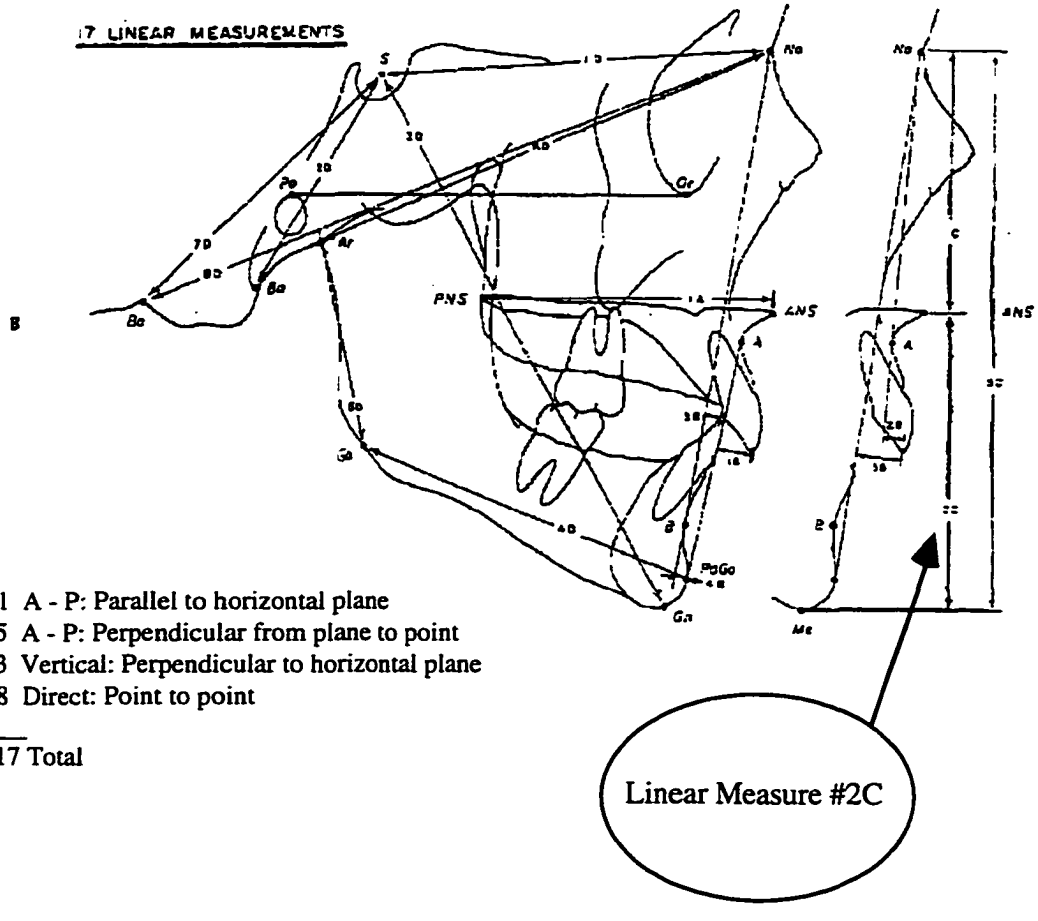


Fig. 3.3. Seventeen Linear Measurements of the Bolton Faces from the Bolton Standards. Reprinted with permission of B. Holly Broadbent and adapted from "Fig.2.B, Diagram illustrating seventeen linear measurements made on the Bolton Faces that were also derived from computerized data by the University of Michigan Biometrics Laboratory" from p. 138 of Broadbent, Broadbent, & Golden, (1975), Bolton Standards of Dentofacial Developmental Growth.

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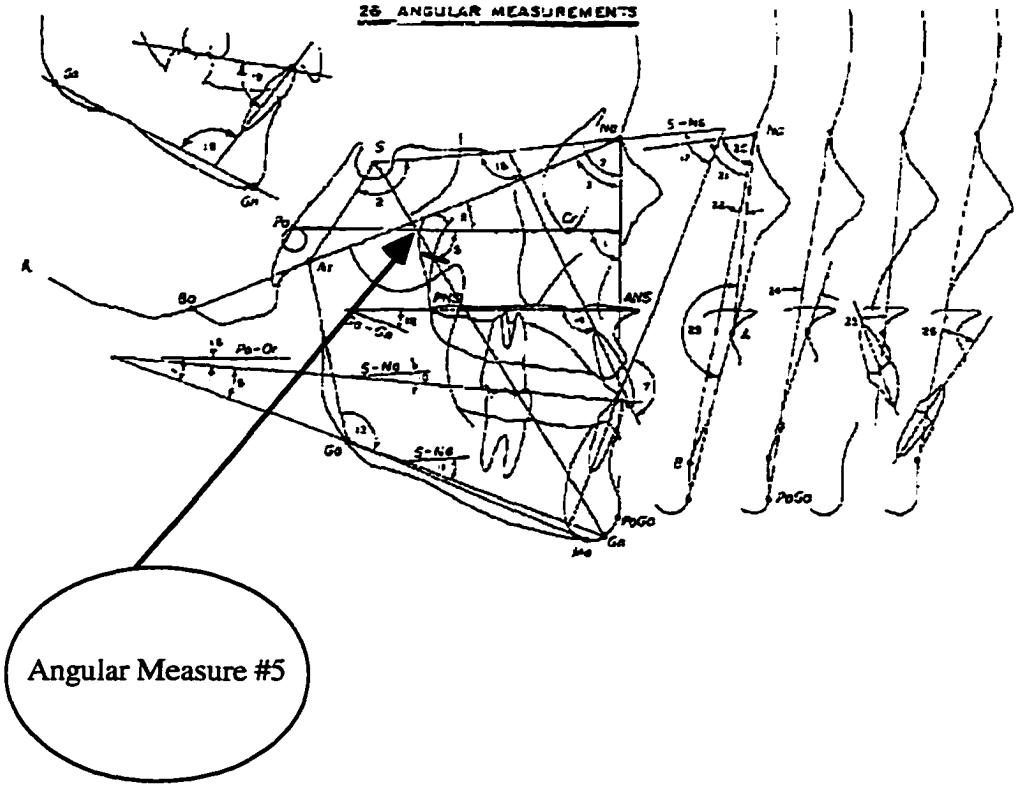


Fig. 3.4. Twenty-Six Angular Measurements Made of the Bolton Faces from the Bolton Standards. Reprinted with permission of B. Holly Broadbent and adapted from "Fig.2. A, Diagram illustrating twenty-six angular measurements made on the Bolton Faces and produced from the computerized Bolton tracings" from p.138 of Broadbent, Broadbent, & Golden, (1975), Bolton Standards of Dentofacial Developmental Growth.

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Further evidence was drawn from Smith and McLean-Muse (1986) who measured maximum oral opening in millimeters in three groups of children and adults. Their findings are summarized in Table 3.6.

Table 3.6.--Maximum Oral Opening in Children and Adults from Smith and McLean-Muse (1986)

	Ages 4 and 5	Ages 7 and 8	Ages 10 and 11	Adults
MAXIMUM ORAL OPENING	42 mm	46 mm	48 mm	46 mm

Based on their measurements in 1986, Smith and McLean-Muse (1987) used one bite-block size for both 4- and 5-year-olds and adults, one which resulted in an IID of 11 mm. Yet, based on Gibbs and Messerman's (1972) measurements, that IID would not place the jaw outside of a typical range for adult speech movements. As stated earlier, Tye, Zimmermann, and Kelso (1983) reported that an 8-mm jaw displacement did not increase tongue movements over the normal condition. One might then argue for the use of a 20-mm bite block for both adults and children. Oller and MacNeilage (1983) did, in fact, use a 15- and a 20-mm bite block with a four-year-old and an eight-year-old, but found that in the eight-year-old the acoustic measurements and perceptual judgments of the vowels produced with a 20-mm bite block differed substantially from those produced with a 15-mm bite block. The four-year-old's productions were too variable to observe clear differences. All of the other bite-block studies in children used an IID of 10 - 12 mm. Gibson and McPhearson (1980) reported that through trial and error, they determined that a 10-mm bite block created a situation for children comparable to that created by a 20-mm bite block for adults.

In view of the lack of unambiguous information about appropriate scaling procedures for children versus adults, a 10-mm IID was chosen for the children, allowing

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direct comparison to Edwards (1992), and remaining within the range of bite-block sizes used in previous studies. A 20-mm IID was chosen for the adults.

Returning to Tables 3.1 and 3.2, it is apparent that a majority of studies placed the bite block between the molars on one side of the mouth. That was deemed a wise choice for this investigation in order to facilitate comparisons across studies.

Finally, while bite-block materials have varied, recent studies have largely used customized bite blocks of dental impression material. These have the virtue of maximally stabilizing a fixed jaw position to prevent both vertical and horizontal movements of the jaw and were chosen for use here.

Details of construction and placement are provided in "Chapter Five: Methods" below.

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CHAPTER FOUR

COMPUTER SIMULATION OF BITE-BLOCK EFFECTS ON FORMANT FREQUENCIES

In order to determine whether or not a speaker is compensating for a bite block, not to mention the degree to which compensation is accomplished, it is necessary to have an estimate of the effect that a bite block would have upon the acoustics of a vowel if the vocal tract were passive. It is not possible for a subject to perform in such a way, but predictions of these effects can be derived from computer simulation. Four previous studies provided information about attempts to do so.

Lindblom and Sundberg (1971a) developed an articulatory model that defined procedures for deriving formant frequencies from information about the state of the lips, position of the jaw, shape and position of the tongue, and larynx height. Place and degree of tongue constriction were controlled separately. The articulatory parameters were related to vocal tract shape and area function and then to acoustic transfer function. Lindblom and Sundberg reported the acoustic and auditory consequences of varying those parameters individually on 13 Swedish vowels, including /i/ and /æ/, of interest here. Their manipulations of jaw opening have relevance for this study. Simulations of the 13 vowels were produced with jaw openings varied between 5 and 23 mm. (It was assumed that the jaw opened 4 mm before the lips parted.) The study did not provide tables of formant values predicted for each vowel at each particular measure of jaw opening, but F1 was reported to rise as the jaw was opened, no matter the vowel. The rise was reported to be substantial - "several hundred Hertz" (p.1174). Lindblom and Sundberg's Figure 12 (p. 1173) provided a plot of F1, F2, and F3 values for the vowel /i/ with increasing jaw opening. Careful examination of the figure revealed that F1 for /i/ was predicted to rise

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from 200 Hz at a 5-mm opening to nearly 450 Hz at a 20-mm opening by virtue of mandible movement alone. F2 was less affected by jaw movement alone, but was extremely sensitive to tongue body positioning. That effect was diminished somewhat as the mandible was lowered, which tended to reduce area contrast along the tract. Again, by carefully examining Lindblom and Sundberg's Figure 13 (p. 1175), illustrations of the effects of jaw opening and tongue body position, it was observed that F2 appeared to drop on the order of 250+ Hz. No tables of actual values were provided.

In two subsequent publications, Lindblom, Lubker, and Gay (1979) and Gay, Lindblom, and Lubker (1981) studied bite-block effects on the Swedish vowels /i,o,u,ɑ/ using predictions from the articulatory model described above. Lindblom, Lubker, and Gay observed that an uncompensated jaw opening of 22.5 mm (interincisor distance) resulted in an increase in F1 of several hundred Hertz. For example, their Table II (p.153) provided simulated values for the vowel /i/ and with a "normal" jaw opening (designated as 9 mm interincisal distance) and with a 22.5-mm jaw opening. Normal F1, F2 and F3 values were 260, 2290, and 2935 Hertz, respectively; bite-block values were 475, 1875, and 2660 Hertz. These represented a 275-Hz rise in F1, a 415-Hz lowering of F2 and a 275-Hz lowering of F3. Gay, Lindblom and Lubker obtained similar values, noting that uncompensated simulations of jaw lowering shift /i/ to /ɛ/-like qualities.

Similarly, Fowler and Turvey (1980) generated a pair of F1 and F2 predictions for each of the six vowels they studied (/i, ɛ, ɑ, ɔ, ʌ, u/) in normal and bite-block conditions. The Haskins Laboratories articulatory synthesizer was used. It, like that of Lindblom and Sundberg (1971a), produced acoustic output based on the area function of a vocal tract analogue. It derived a set of formant frequencies from information on the state of the vocal tract as shaped by position of the tongue body, velum, tongue tip, jaw, lips and hyoid bone. Fowler and Turvey first synthesized a vowel that was of adequate perceptual quality. Then the position of the model's jaw was adjusted to the value it would have with a 14-mm bite block clenched between the teeth. The vowel was then re-synthesized. The

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difference between initial and new values of F1 and F2 represented changes that would occur if the talker made no effort to compensate for the bite block. For /i/, normal F1 and F2 values were calculated at 328 Hz and 2238 Hz respectively; bite-block values were simulated at 701 Hz and 1943 Hz.

Lindblom and Sundberg (1971a) provided no tables of formant values for /i/ and /ae/ at a 20-mm jaw opening and Fowler and Turvey (1980) provided values only for /i/ with a 14-mm jaw opening. The values obtained from Lindblom, Lubker, and Gay (1979) and Gay, Lindblom, and Lubker (1981) were the result of a 22.5-mm jaw opening. Therefore, it was necessary to use the Haskins Laboratories articulatory synthesizer to produce simulations of the three vowels used in this study, /i/, /I/, and /ae/, first with a characteristic vocal tract configuration and interincisal distance and then with a 20-mm interincisal distance, in order to predict the effect of this size bite-block on these specific vowels, given no compensation.

The Haskins Laboratories synthesizer calculated formants based on the area function of an analogue of an adult vocal tract. It was, therefore, not possible to determine what the effects of a 10-mm bite block on a four-year-old's vocal tract would be.

An additional special problem needed to be addressed with regard to the speakers with hearing impairment. Their *normal* productions of the vowels studied here differed in some ways from vowels synthesized as representative of these phonemes. It was necessary to synthesize formant frequency values for two additional vowels because several hearing-impaired speakers' characteristic productions of two of these three vowels in the normal condition resulted in /ɛ/-like productions of the vowel /I/ and /ɑ/-like productions of the vowel /æ/. Therefore, the characteristic tract configurations for the five vowels /i, I, ɛ, æ, ɑ/ were synthesized to obtain values of formant frequencies at a normal interincisor distance. The interincisor distance, a newly available calculation added to the Haskins Laboratories articulatory synthesizer software, was then manipulated to simulate the effect of a 20-mm interincisal distance upon those configurations. These vowels were

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then re-synthesized, and the resultant changes in formant values were obtained, as seen in Table 4.1.

Table 4.1.--Computer-Simulated Formant Values for Normal and Bite-Block Vowels

	/i/	/ɪ/	/ɛ/	/æ/	/ɑ/	
F2 in Hz	2247	2109	2066	1685	1248	Normal
F2 in Hz	1969	1781	1839	1636	1209	Bite Block
Δ Hz	↓ 278	↓ 328	↓ 227	↓ 49	↓ 39	
F1 in Hz	330	398	510	781	880	Normal
F1 in Hz	671	778	740	820	869	Bite Block
Δ Hz	↑ 341	↑ 380	↑ 230	↑ 39	↓ 11	

Simulation of the bite-block condition resulted in a decrease in second formant values for all vowels, with the greatest effect for the close vowels /i/ and /ɪ/ and the least effect for the open vowels /æ/ and /ɑ/. Simulation of the bite-block condition resulted in an increase in first formant values for /i/, /ɪ/, /ɛ/, and /æ/, again with the greatest effect for the close vowels /i/ and /ɪ/ and the least effect for the open vowel /æ/.

The seemingly inconsistent decrease in the F1 value for /ɑ/ in the simulation of the bite-block condition illustrated well the effect of having a bite-block interincisor distance that is close to, or, in fact, less than the normal interincisor distance for an open vowel. If the bite-block interincisor distance were less than that in normal production, the jaw would be higher, carrying the tongue body higher in the vocal tract, resulting in a lowered F1 value.

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This point may be further illustrated by simulating the effects of two arbitrarily chosen interincisor distances on the formant values for /æ/, the open vowel used in this study. Simulated effects are shown in Table 4.2.

Table 4.2.--Computer-Simulated Formant Values for /æ/ at Varying Interincisor Distances

	Normal Interincisor Distance	Interincisor Distance 4mm More Open than Normal	Interincisor Distance 1mm Less Open than Normal
F2 for /æ/	1685	1636	1690
Δ Hz	N/A	↓49	↑5
F1 for /æ/	781	820	777
Δ Hz	N/A	↑39	↓4

It can be seen that the formant values for the open vowel /æ/ may be either raised or lowered in a bite-block condition, depending on whether the bite block creates a less-than-normal or greater-than-normal interincisor distance.

The predictions generated here served as a back-drop against which to compare obtained vowel formant frequency measurements of subjects' speech productions in order to judge whether and to what degree compensation was accomplished for a bite block.

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CHAPTER FIVE

METHODS

Subjects

The research paradigm was applied to four separate subject groups, each of which are described in sequence below.

Adults with Normal Hearing

Two female and four male adults, with normal hearing, served as subjects in this study. They were matched exactly for sex and matched generally for age (+/- 2 years in five cases, and +10 years in one case (N6M[1])) with the subjects with profound hearing loss. Because the results from adults with severe hearing impairment were expected to be most like those from adults with normal hearing, and because the results from subjects with profound hearing impairment were expected to be least similar, the controls were matched to the profoundly hearing-impaired group. Their ages ranged from 24 to 62 years. (See Table 5.1.) These individuals had no atypical speech characteristics and no reported history of neurological abnormality. All exhibited normal middle ear function as determined by tympanometric screening performed by the experimenter. Four were able to pass an air conduction hearing screening, also performed by the experimenter, at 25 dB HL for the frequencies 500, 1k, 2k, 4k, and 6kHz. Two subjects exhibited very mild high frequency loss. N3M, aged 62 years, exhibited thresholds of 30 dB at 4k and 40 dB at 6kHz in the left ear. Subject N4F, aged 51 years, exhibited a threshold of 30 dB at 4kHz

[1]Coding for all subjects in this study was done using two letters and one number. The first letter indicated subject group (N=Adults With Normal Hearing; C=Children With Normal Hearing; P=Adults With Profound Hearing Loss; S=Adults With Severe Hearing Loss). The middle number indicated subject number within subject group. The final letter indicated sex of the subject (M=Male; F=Female).

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in her left ear. These thresholds were considered within normal limits for the subjects' age group.

The subjects' primary language was English. The female subjects, N2F and N4F, were from Chicago and Minneapolis, respectively. N1M and N6M were from western Canada (Saskatchewan and Alberta, respectively) and N5M was from central Canada (Ontario). N3M was from the New York metropolitan area. These speakers were not expected to differ in production of the three vowels examined in this study (/i/, /I/, /æ/) in the context of the carrier phrase used ("Say hVt again"), and, indeed, the experimenter heard no differences in production among the subjects. Most tokens produced by these speakers were characterized by a flap production (/ɾ/) of final /t/ in "hVt again."

Children with Normal Hearing

Three female and three male preschool children between the ages of 3 years, 10 months and 4 years, 10 months served as subjects in this study. (See Table 5.1.) They had at least average intelligence, as determined by school records, and no known handicapping condition affecting motor or neurological development. They were from homes where the primary spoken language was English, and were judged by a speech pathologist to have normally developing speech and language skills. Each was able to pass an air conduction hearing screening test, performed by the experimenter, at 25 dB HL at each of four test frequencies (1k, 2k, 4k, and 6kHz), using procedures described by Northern and Downs (1974). The parents of Subject C3F reported that she had had frequent ear infections in the past, but her hearing was within normal limits at the time of screening. Tympanometric screening, though desirable, was not feasible because equipment was difficult to transport to the preschool location where testing was done.

Five of the subjects were enrolled in a preschool program in the New York metropolitan area. The sixth, C6F, resided in New Haven, Connecticut. As with the adults with normal hearing, the children were not expected to differ in production of the

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three vowels examined in this study in the context of the carrier phrase used, and the experimenter heard no such differences. The parents of the subjects were largely upper middle class professionals. Four other children from the preschool program in New York participated in portions of this study, but did not ultimately serve as subjects; three children proved unable or unwilling to complete all tasks of the study, and one child was judged to have delayed speech and language skills and was referred for appropriate speech-language assessment and follow-up.

Adults with Profound Hearing Loss

Two female and four male adults with profound hearing loss served as subjects in this study. Profound hearing loss is defined here as an average hearing loss, or Pure Tone Average (PTA), between 91 and 120 dB HL at 500, 1k, and 2kHz. The profoundly hearing-impaired adult group was generally balanced, though not strictly matched, for sex and age, with the severely hearing-impaired adult group. The profoundly hearing-impaired group ranged in age from 24 to 60 years. (See Table 5.1.) Other than their hearing impairment, these subjects had no other known condition affecting motor or neurological development. Five subjects had attended Clarke School in Northampton, Massachusetts, an oral/aural school for the hearing impaired, where they had received consistent speech training throughout their school years. Subject P2F had attended Lexington School for the Deaf in New York, New York, when it offered only oral/aural programs for the hearing impaired and where she, too, had received consistent speech training throughout her school years. Although regional linguistic influences might be expected to affect these speakers' articulation, they were not expected to differ in production of the three vowels examined in this study (/i/, /ɪ/, /æ/) in the context of the carrier phrase used ("Say hVt again"), and, indeed, the experimenter heard no such differences.

At the time of speech production testing, each subject received a complete audiological evaluation from a certified audiologist at Clarke School, the oral/aural school

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previously attended by five of the profoundly hearing-impaired speakers. The evaluation included air conduction testing at 250, 500, 1k, 2k, 4k, and 8kHz, bone conduction testing where appropriate, speech discrimination testing using either NU-6 or AB word lists, and tympanometry. Bone conduction and tympanometry were used to determine, as far as possible, that there were no significant conductive overlays. Because the school audiologist performed the testing, it was possible to obtain an audiological history of cause, severity, and stability of hearing loss for five of these subjects. All were believed to have had profound hearing loss from birth. Average hearing loss, in the better ear, ranged from 98 to 110 dB HL. (See Table 5.2.) Better-ear audiograms for each subject are provided in Figure 5.1 (a - f).

One other adult with a profound hearing loss, also a graduate of Clarke School, participated in this study, but did not ultimately serve as a subject. The experimenter, at the time of speech recording, made an informal judgment that this subject's speech skills did not enable him to adequately perform the experimental task, that is, to make reliable distinctions between the three vowels examined. Formal intelligibility ratings, described in the following section of this chapter, were obtained for a speech sample from this subject. He received a 3% word intelligibility rating from inexperienced listeners. That low score was considered validation of the experimenter's informal judgment that this subject failed to demonstrate ability to perform the experimental task adequately, and his data were removed from analysis.

Adults with Severe Hearing Loss

Three female and three male adults with severe hearing loss served as subjects in this study. Severe hearing loss is defined here as an average hearing loss, or Pure Tone Average (PTA), between 61 and 90 dB HL at 500, 1k, and 2kHz. The severely hearing-impaired adult group was generally balanced, though not strictly matched, for sex and age, to the profoundly hearing-impaired adult group. The ages of the severely hearing-impaired

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adults ranged from 19 to 45 years. (See Table 5.1.) Other than their hearing impairment, these subjects had no other known condition affecting motor or neurological development. All had attended Clarke School in Northampton, Massachusetts, the same oral/aural school for the hearing-impaired attended by five of the adults with profound hearing impairment, where they received consistent speech training throughout their school years. Subject S6F also had spent many of her school years in mainstreamed settings where she received speech-language services. Although regional linguistic influences might be expected to affect these speakers' articulation, they were not expected to differ in production of the three vowels examined in this study (/i/, /ɪ/, /æ/) in the context of the carrier phrase used ("Say hVt again"), and, indeed, the experimenter heard no such differences.

At the time of speech production testing, each subject received a complete audiological evaluation from the certified school audiologist who provided the audiological evaluation for the subjects with profound hearing loss. The hearing evaluations for both groups were the same in all respects. All adults with severe hearing impairment were believed to have had hearing loss from birth. Three-frequency average hearing loss (500, 1k, 2kHz), in the better ear, ranged from 63 to 92 dB HL. (See Table 5.2.) Better-ear audiograms are provided for each subject in Figure 5.1 (g - l). Previous audiological records revealed that S1M, S2M, and S4M experienced gradually increasing hearing loss: S1M from a moderate (PTA 50 dB) to a borderline severe-to-profound loss (PTA 90 dB), S2M from a severe loss (PTA 72 dB) to a borderline severe-to-profound hearing loss (PTA 87 dB), and S4M from a moderate (PTA 50 dB) to a sloping severe hearing loss (PTA 63 dB).

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Table 5.1.--Age and Hearing Status of All Speakers

SPEAKER	AGE	HEARING STATUS
Adults with Normal Hearing		
N1M	31	Normal
N2F	25	Normal
N3M	62	Mild loss at 4/6kHz; left ear
N4F	51	Mild loss at 4kHz; left ear
N5M	24	Normal
N6M	46	Normal
Children with Normal Hearing		
C1F	4 yr.; 07 mo.	Normal
C2M	4 yr.; 08 mo.	Normal
C3F	3 yr.; 10 mo.	Normal
C4M	4 yr.; 01 mo.	Normal
C5M	4 yr.; 10 mo.	Normal
C6F	3 yr.; 10 mo.	Normal
Adults with Profound Hearing Loss		
P1M	60	110 dB HL (PTA)
P2F	51	107 dB HL (PTA)
P3M	29	107 dB HL (PTA)
P4M	24	98 dB HL (PTA)
P5F	26	107 dB HL (PTA)
P6M	36	107 dB HL (PTA)
Adults with Severe Hearing Loss		
S1M	30	90 dB HL (PTA)
S2M	45	87 dB HL (PTA)
S3F	35	92 dB HL (PTA)
S4M	26	63 dB HL (PTA)
S5F	37	91 dB HL (PTA)
S6F	19	68 dB HL (PTA)

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Table 5.2.--Nature of the Hearing Loss of Speakers with Hearing Impairment

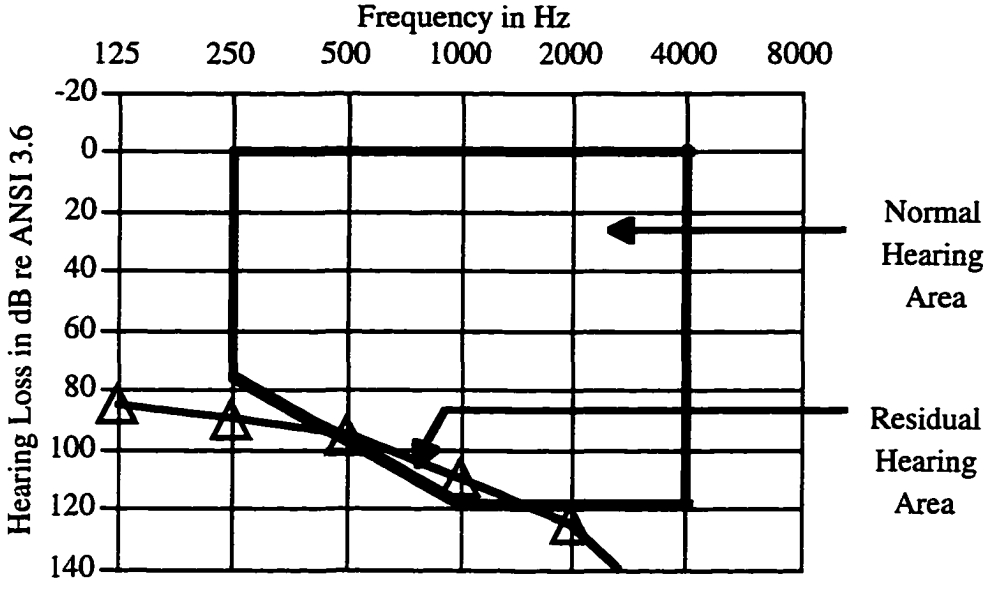
SPEAKER	BETTER EAR PTA dB HL	ETIOLOGY	SPEECH DISCRIMINATION SCORES
Adults with Profound Hearing Loss			
P1M	110	unreported	<10% NU-6[2]
P2F	107	unreported	<10% NU-6
P3M	107	probably genetic	<10% AB[3]
P4M	98	maternal rubella	<10% AB
P5F	107	maternal rubella	<10% AB
P6M	107	probably genetic	13% AB
Adults with Severe Hearing Loss			
S1M	90	RH incompatibility	52% NU-6
S2M	87	probably genetic	16% NU-6
S3F	92	unreported	12% AB
S4M	63	maternal rubella	76% AB
S5F	91	unreported	32% AB
S6F	68	unknown	76% NU-6

[2]Speech discrimination scores, using NU-6 words spoken in the carrier phrase "Say the word ____," were calculated as % whole words correctly recognized.
[3]Speech discrimination scores, using AB words spoken in isolation, were calculated as % phonemes correctly recognized, but reported as % words correct in PB Max equivalents (the highest speech discrimination score for phonetically balanced words).

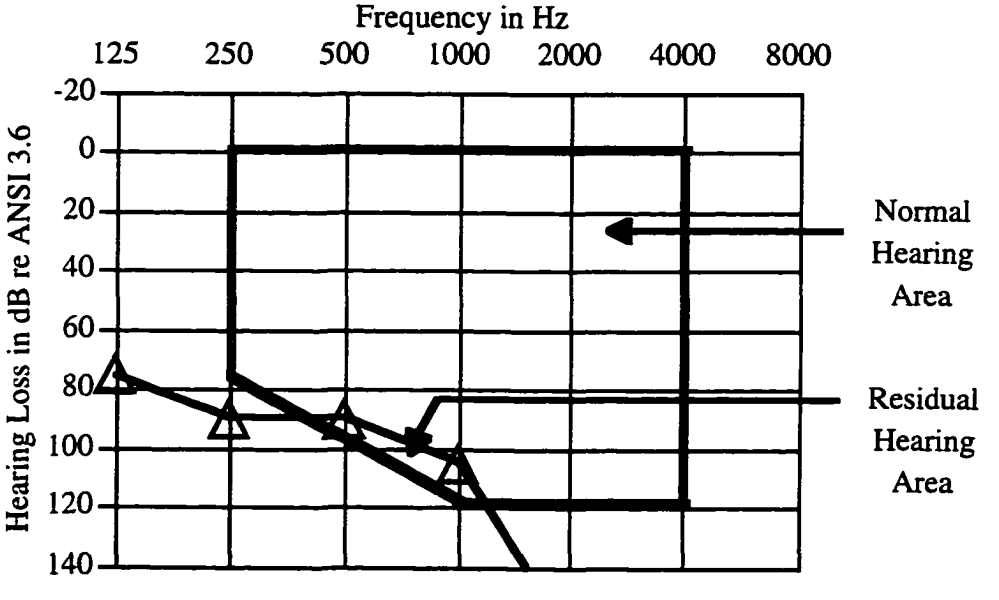
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Fig. 5.1. Better-Ear Audiograms of Speakers with Hearing Loss (a - l)

(a and b)



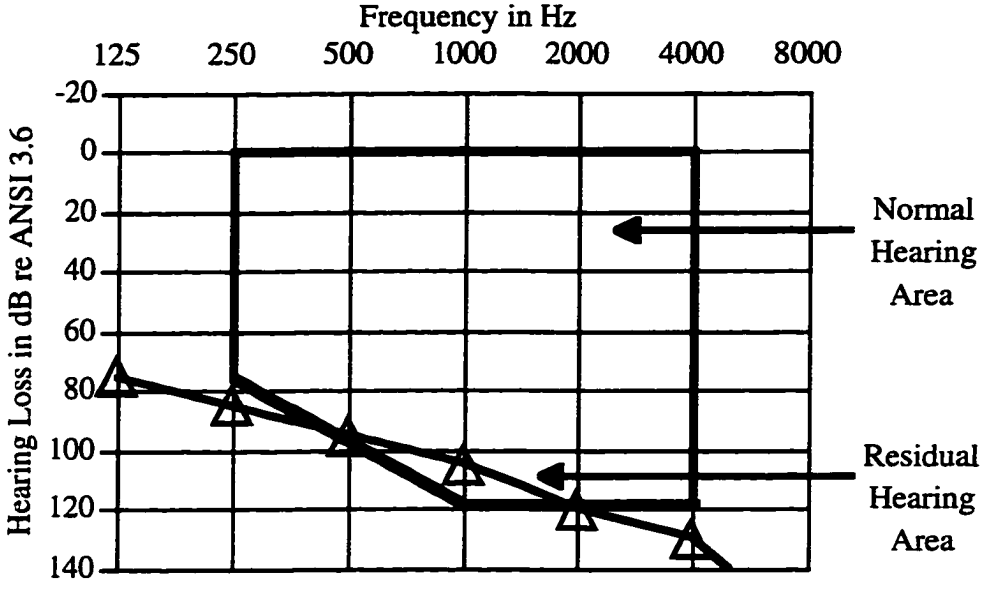
Subject P1M



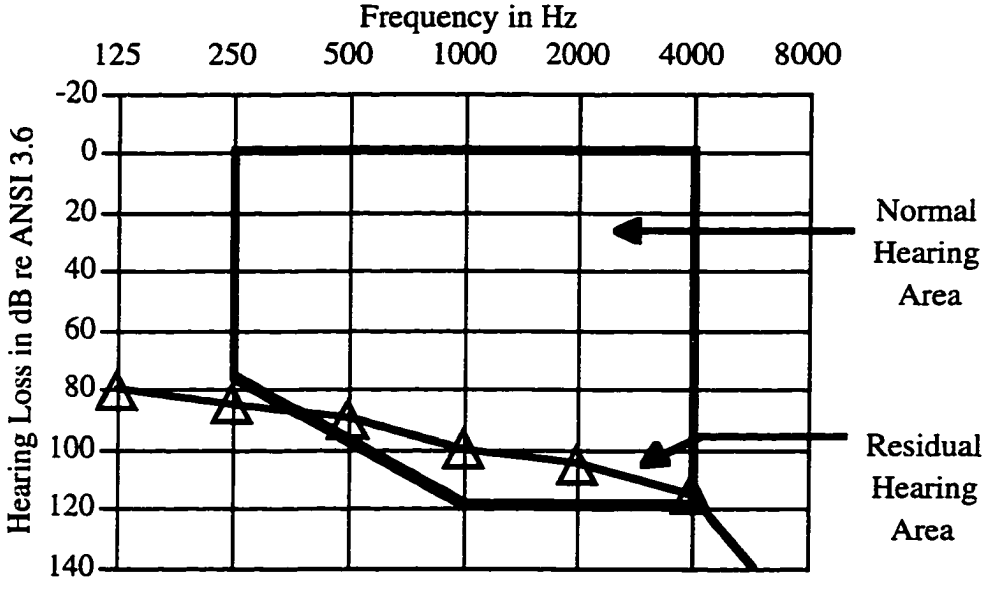
Subject P2F

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(c and d)



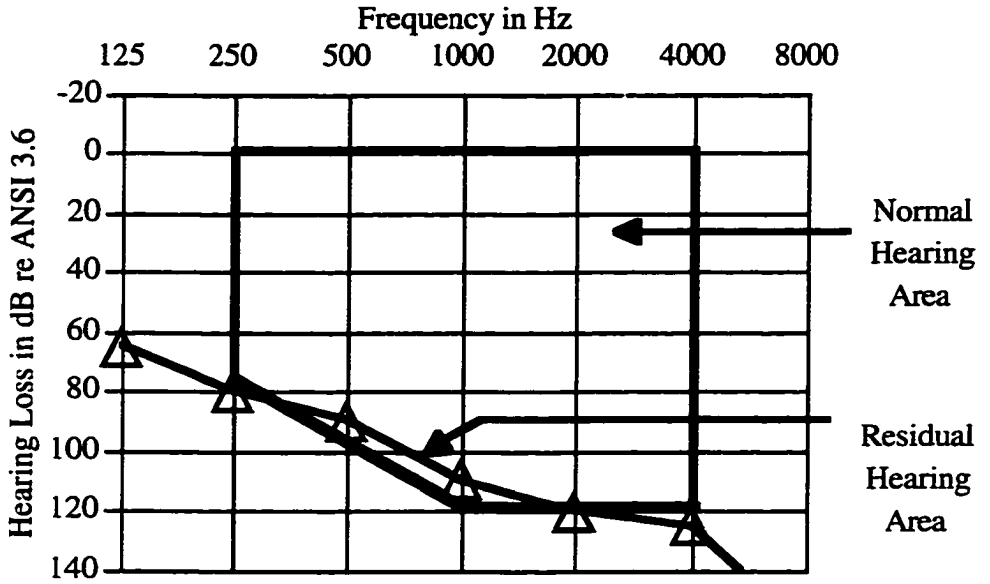
Subject P3M



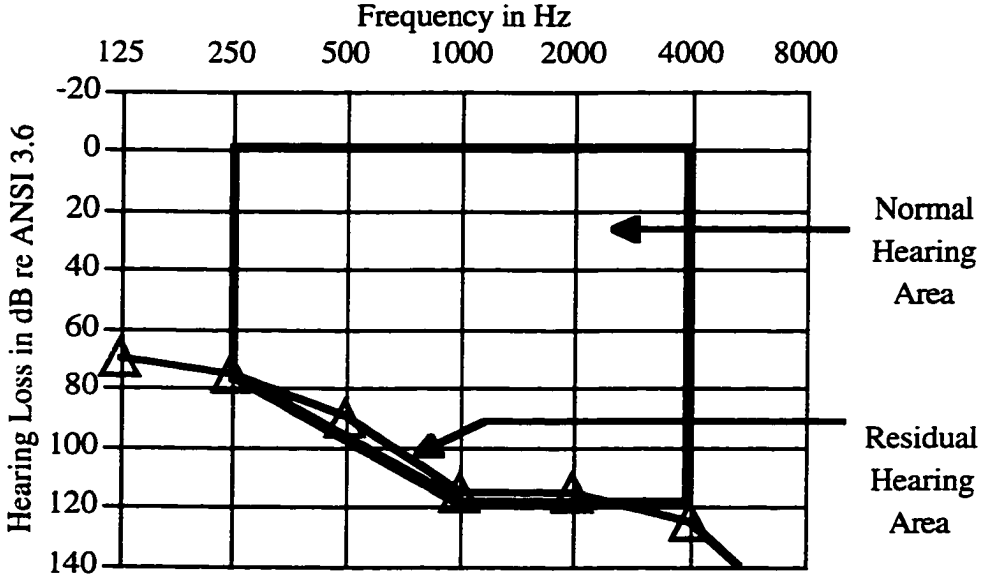
Subject P4M

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(e and f)



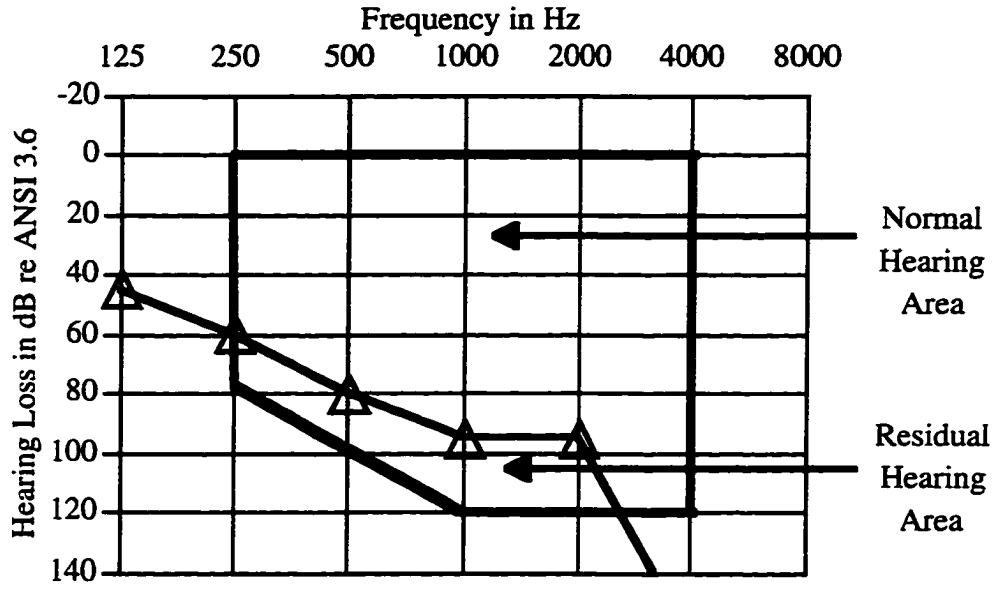
Subject P5F



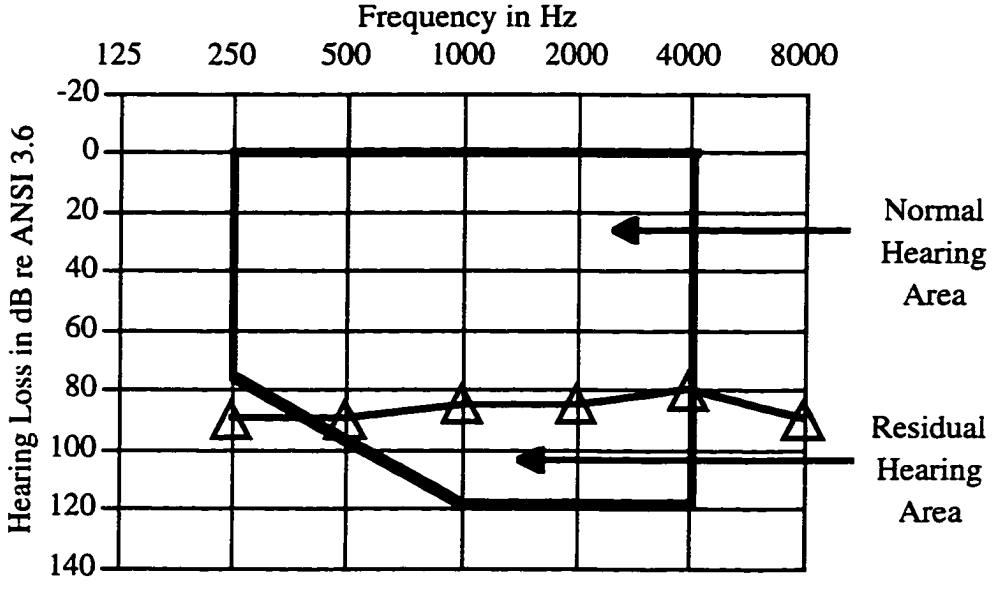
Subject P6M

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(g and h)



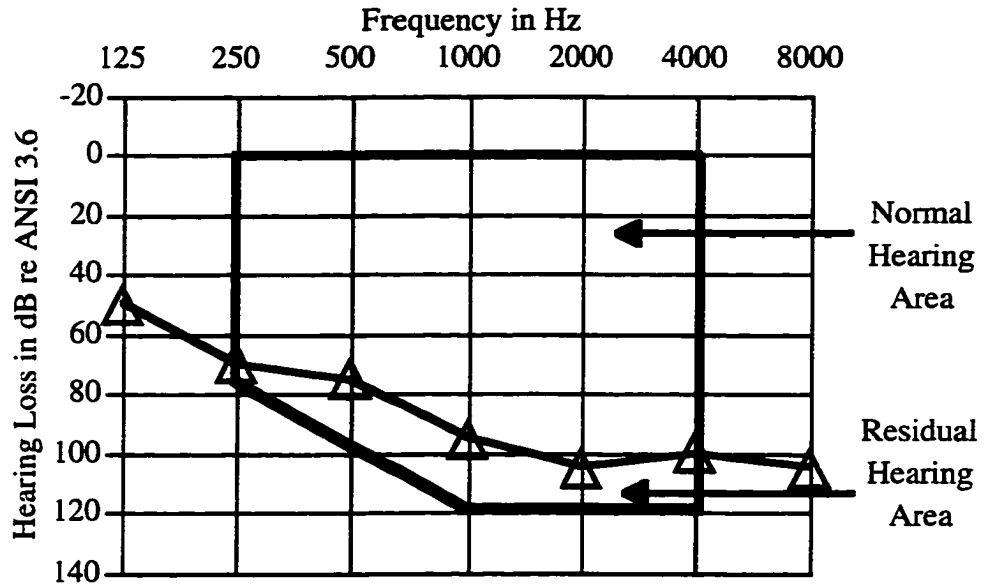
Subject S1M



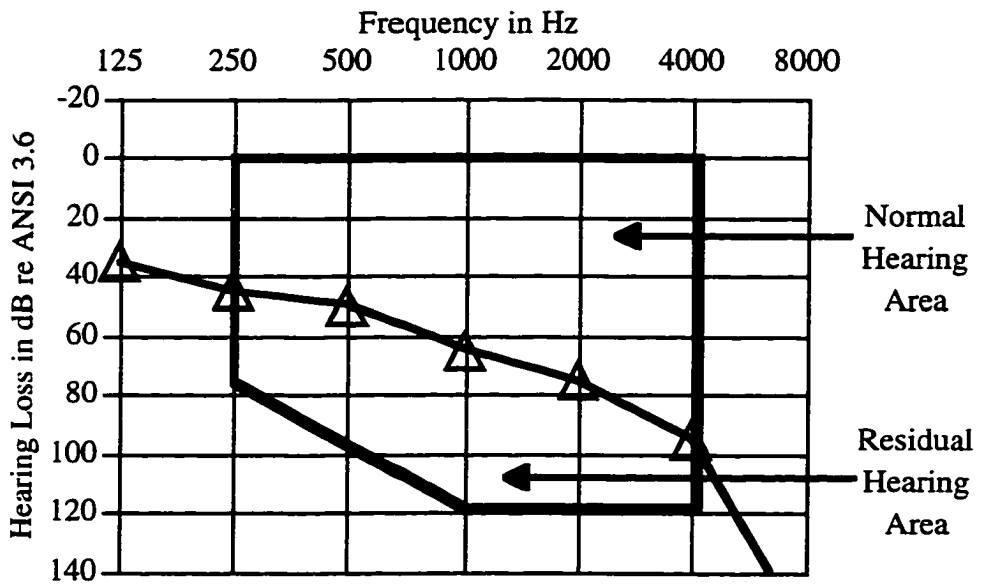
Subject S2M

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(i and j)



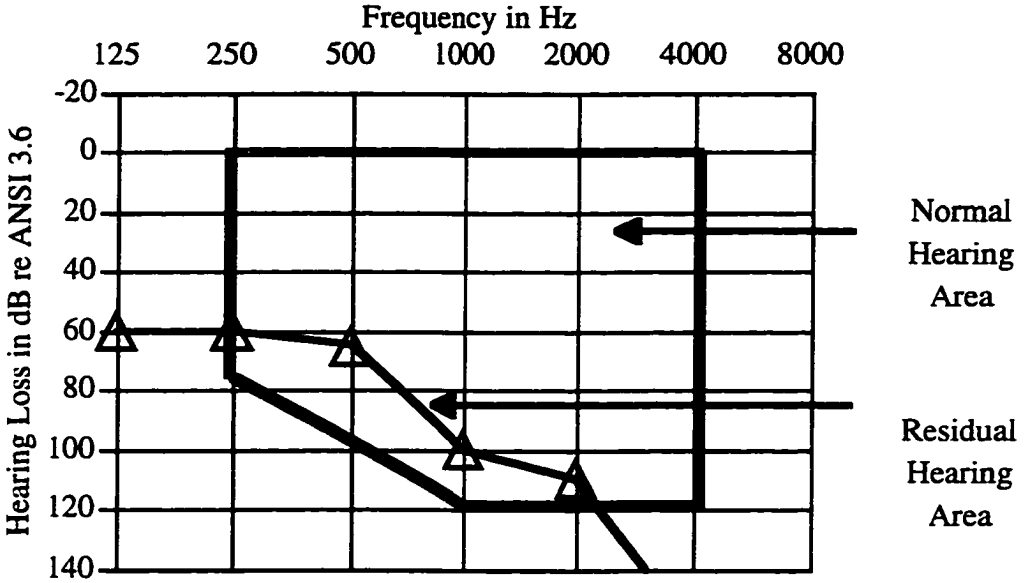
Subject S3F



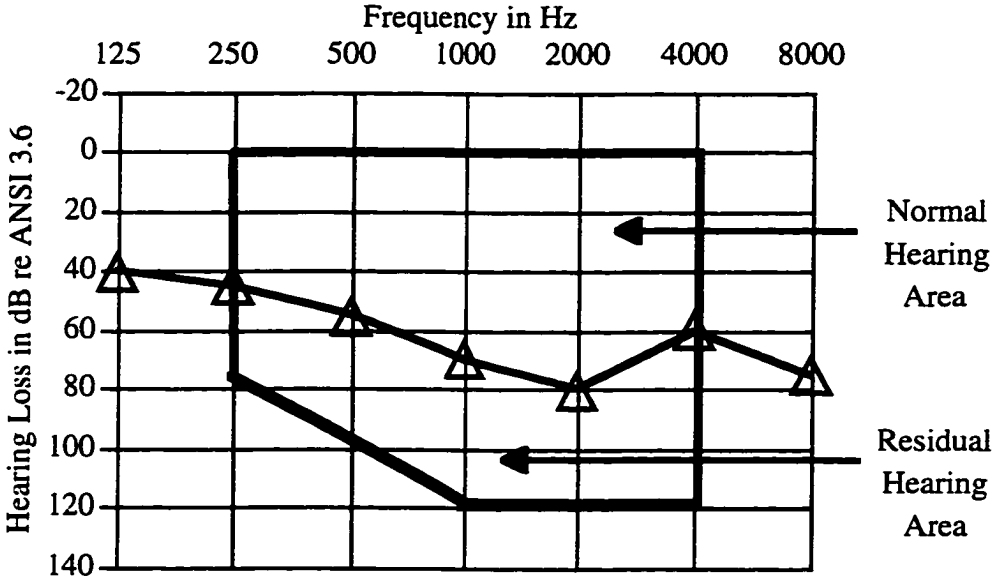
Subject S4M

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(k and l)



Subject S5F



Subject S6F

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Stimuli

The rationale for the use of the vowels /i/, /I/ and /ae/ in the carrier phrase "Say hVt again" was provided in "Chapter Two:Stimuli-Literature Review and Rationale" above.

Four short lists of the three test vowels were generated. Each contained four tokens of each of the vowels, resulting in a total of 12 tokens per list. These 12 tokens were drawn from a hat a total of four times, creating four short-list versions. (See Appendix A.) The four short lists were then randomized to create four long lists of 48 tokens each. (Again, see Appendix A.) The four long lists were randomized across the four test conditions. Thus the order in which the vowels were spoken by subjects was randomized within and across speakers.

Each long list provided 16 tokens of each vowel per condition yielding a total of 192 tokens per talker (3 vowels x 16 tokens x 4 conditions) and 4608 tokens in all (192 tokens x 24 speakers). All vowel tokens were produced in the carrier phrase "Say hVt again".

Bite Blocks

Scaling

As discussed in "Chapter Three: Bite Blocks: Literature Review and Rationale", an interincisal distance of 20 mm was chosen for the adult subjects and a 10-mm interincisal distance was chosen for the children.

Construction

Construction of all bite blocks was done following procedures outlined by Netsell (1985). Those procedures resulted in a bite block that was customized for each subject, not only ensuring a standard interincisal distance (IID), but also the restraint of lateral or anterior/posterior movements of the jaw. The method also ensured that the jaw stayed closed in a position that was on the normal path of vertical opening and closing. The preparation involved five main steps:

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1. Preparation of the Subject: The experimenter showed subjects her own bite block and how it fit between the teeth. Then the subject practiced opening the jaw and closing it several times with attention to bringing the jaw upward on a normal straight path to occlusion.

2. Presentation of the Tongue Depressor: A tongue depressor was given to the subject. For children, one end of the tongue depressor had been trimmed to an interincisal distance of 10 mm. The wooden tongue depressors were 19 to 20 mm wide (each one varied slightly within that range). Therefore, the tongue depressors used with adults did not require notching. The jaw-closing rehearsal was repeated with either the notched or unnotched tongue depressor turned sideways and placed between the top front teeth. Subjects practiced holding that position for approximately 30 seconds. In the case of the children, bubble gum was used to simulate the dental impression material, as in Edwards (1992). The child practiced bringing the jaw upward and biting gently but firmly on the tongue depressor and the gum placed on the left side of the mouth between the teeth.

3. Preparation of the Compound Material: Two different impression putty materials were used, one for children and one for adults. They yielded the same kind of product, that is, a rubbery, but firm, customized block. However, they differed in "set-up" time. Citricon putty was used for the children. It partially set within 30 seconds, meaning that the child was required to bite on the tongue depressor and hold that position for that amount of time, a realistic expectation for four-year-olds. The block then required time to set up for about 30 minutes before being trimmed. This was not problematic in that sessions with children were, of necessity, scheduled for short periods of time over several days. The 3M material, on the other hand, had a 4-minute, set-up time in the mouth, but was firm enough to be trimmed and to be put into use immediately. This did not prove to be a problem for adults and enabled testing in bite-block conditions to be done within the same session as the construction of the bite block. Each had its distinct mixing requirements, but both consisted primarily of mixing putty with accelerator materials in specific quantities.

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4. Formation of the Bite Block: Using sterile gloves, the experimenter placed the soft rectangular-shaped bite block posterior to the subject's lower left canine tooth. The tongue depressor was then placed sideways between the upper central incisors and the subject carefully raised the jaw until the lower incisors met the edge of the tongue depressor. This position was held for the required "set-up" time.

5. Final Touches: The bite block was trimmed and notched for the wrapping of a piece of dental floss around it as a safety precaution and a method of easy removal.

Placement

Construction of bite blocks according to the Netsell procedure (1985) ensured that the customized block was worn in an identical fashion each time it was used. It was always placed posterior to the lower left canine tooth and was trimmed so as not to interfere with lingual movement or to obstruct the air stream at the front of the mouth. In addition, because it was customized, the teeth fit into the impression material such that the block could not be rolled between the teeth. Horizontal as well as vertical movements of the jaw were prohibited.

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Instrumentation

For Audiological Screening and Testing

The hearing acuity of the children and adults with normal hearing was screened using a Beltone Series 100 Portable Audiometer (Model 112) with TDH50 earphones. It was calibrated with regard to SPL output in decibels at each test frequency, keeping the loudness selection dial at a constant 70dB setting. The audiometer also was calibrated with regard to attentuator linearity by selecting a tone (500 Hz or 1kHz) and measuring the output in dB SPL at each loudness level marked on the dB setting dial. This was done using a 500 gram weight placed on the TDH50 earphone over a 6-cc coupler connected to a Bruel and Kjaer sound level meter. The audiometer was calibrated three times over the course of testing the twelve subjects and was found to comply with ANSI 1969 standards on each occasion. See Table 5.3 below.

Table 5.3.--Calibration of Portable Audiometer

Normal Calibration Level Re:ANSI TDH 50	Frequency in Hertz	Output in dB SPL at 70 dB Hearing Level					
		First Calibration		Second Calibration		Third Calibration	
		Left	Right	Left	Right	Left	Right
117.6	125	117.5	117.5	117.8	117.6	117.9	117.7
96.7	250	98.0	98.0	98.1	98.0	98.4	98.1
83.5	500	84.0	84.5	84.4	84.4	84.5	84.3
77.4	1000	77.5	77.5	78.4	78.0	78.6	78.0
81.1	2000	81.5	82.0	81.6	81.6	81.8	81.6
80.7	4000	82.0	82.0	82.3	82.0	82.6	82.1
83.4	6000	DNT	DNT	84.4	83.6	85.6	84.8
83.0	8000	80.5	82.5	81.0	82.3	83.7	84.7

A Grason-Stadler GSI 28 Auto Tymp acoustic immitance screening instrument was used to screen the middle-ear status of the adults with normal hearing. Daily calibration tests were conducted on the test cavity provided with the device and on the ear of the

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experimenter for a day-to-day biological reference of the probe and stimulus tones as well as the air pressure system. The instrument was found to comply with the ANSI S3.6-1969 standard for aural acoustic immitance instruments.

All subjects with hearing impairment received complete audiological testing by a certified audiologist at Clarke School (previously attended by eleven of the twelve subjects) using audiological instruments and sound booths in the School's audiological clinic.

For Presentation of Masking Noise

A portable noise generator designed and developed by Arthur Boothroyd and his research staff at the Graduate Center of the City University of New York (CUNY) was used to prevent subjects from hearing their own speech, via air conduction, during the masking and masking-plus-bite-block conditions. A set of Realistic Nova 40 headphones was coupled to the noise generator. The generator was used to produce pink noise (constant level/octave) because it contains more low frequency noise than white noise (constant level/cycle) and was, thus, a more efficient masker of vowels.

The "A" volume setting of the generator was used. Three noise generator units were used over the course of testing the four subject groups. Each was calibrated for pink noise output levels at the "A" volume setting and the "stereo" sound delivery setting, through right and left headphones, using a 500 gram weight placed on the respective TDH50 earphone over a 6-cc coupler connected to a Bruel and Kjaer sound level meter. CUNY Unit #1 was used with the children. Its measured output was 81.5 dB SPL, right and left phones. CUNY Unit # 5 was used with the subjects with severe and profound hearing loss. Its measured output was 89.5 dB SPL, right and left phones. CUNY Unit #2 was used with the adults with normal hearing. Its measured output was 83 dB SPL for the right phone and 83.7 for the left phone. These levels appeared to mask speech effectively and were well within OSHA standards of safe loudness levels for noise

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exposure. It should be noted, however, that it is not possible to confirm complete masking objectively.

For Monitoring Subjects' Speech Intensity Levels

In order to observe the effects of auditory feedback interruption on speech production, a method was required for the investigator and the subjects to monitor the intensity level of spoken utterances. The goal was to prevent subjects from "over-shouting" the masking noise presented through earphones in the masking-noise and bite-block-plus-masking-noise conditions.

For all adult subjects, the recording-level meter of the tape recorder was used as a monitoring device. The meter was set such that the peaks of speech utterances deflected the needle of the recording-level meter from 0 dB to +5 dB for chromium dioxide audio tape or +8 dB for metal tape, allowing the deflection of the needle to be as large as possible without reaching peak levels. Adult subjects were instructed to maintain speech levels in that range during all conditions, but to exercise greatest care in those conditions in which masking noise was used.

For the children, a sound-level detector developed by Arthur Boothroyd and his research staff at The Graduate Center of the City University of New York was used. The device featured an input microphone and two level set pots that provided for adjustment of the "turn-on" threshold for a pair of indicator lights, one red and one green. The sound-level detector device was placed in line with the microphone and set to levels that indicated to the subject when he was speaking loud enough (green light) or too loud (red light) to be within an appropriate range. While subjects were reciting a nursery rhyme, the range was determined by monitoring the recording-level meter on the tape recorder. The green light was set to turn on when the needle of the meter was deflected to between 0 and +5 dB and the red light was set to turn on when the needle deflected to values exceeding that desired range.

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Results of calibration of the sound-level detector indicated that the overlap range for the two lights was typically 1 - 3 dB and the thresholds varied approximately linearly. With a white noise input, the green light at pot setting 1.5 came on at about 68 dB and the red light at pot setting 2.5 came on at about 77 dB. Those settings were selected as starting points from which adjustments for each speaker were made.

For Speech Recording

Over the course of testing the four subject groups, three high quality tape recorders were used to record speech. The first was a Uher portable reel-to-reel tape recorder (Model 4200) was used to record the speech of the children. A dynamic omnidirectional microphone, Electrovoice Model 635A; Serial #8846, was coupled to the Uher recorder.

The same Uher recorder was used to record the speech of four of the six adults with normal hearing. As for the children, a dynamic omnidirectional microphone, Electrovoice Model 635A; Serial #8434, was coupled to the Uher recorder. Near the completion of recording this group of subjects, there was a malfunction of the Uher recorder that required a change in equipment. Subjects N5M and N6M were recorded on a Panasonic portable digital tape recorder (Model SV-255) with a 48kHz sampling rate. The Electrovoice microphone, Model 635A, Serial #8434, was used with the digital tape recorder.

A Marantz portable cassette recorder (Model PMD430) was used to record subjects with hearing impairment. The Electrovoice, Model 635 A; Serial #8846, was used with it.

The frequency response of the Electrovoice microphone, Model 635A; Serial #8846, coupled to either the Uher or the Marantz recorder, was obtained using a Bruel and Kjaer sweep frequency sine random generator (Model 1024), a condenser microphone (Model 4145), a microphone amplifier (Model 2603), and a graphic level recorder (Model 2305). The same equipment was used to obtain the frequency response of the Electrovoice microphone, Model 635A, Serial #8434, coupled to either the Uher or the Panasonic tape recorder. A block diagram of the system used for all calibration procedures for every

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combination of tape recorder and microphone appears in Figure 5.2 and the obtained frequency response of each equipment configuration appears in Figures 5.3 to 5.6.

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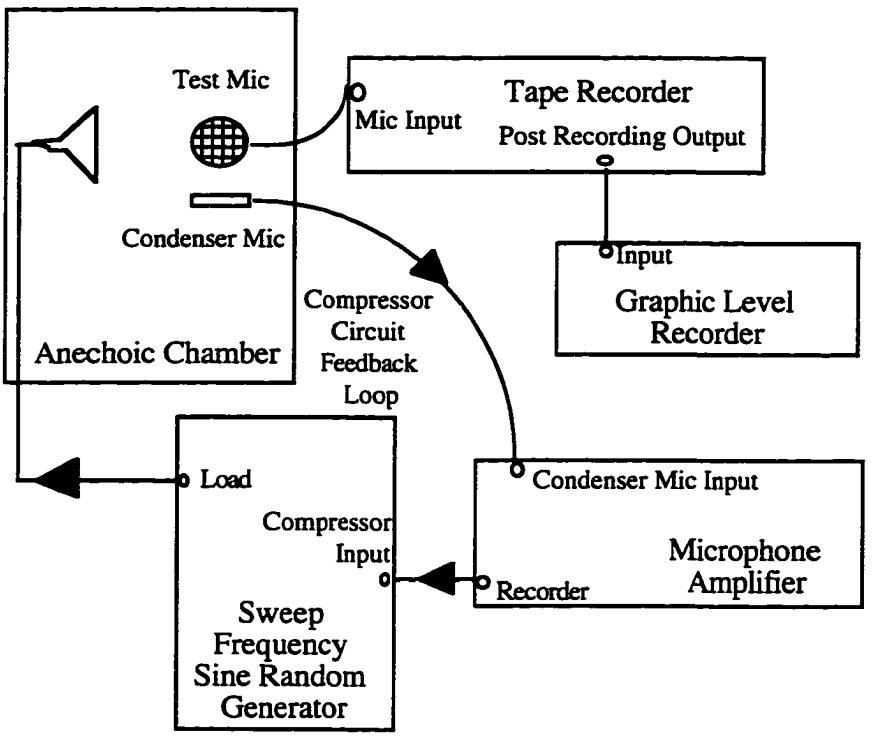


Fig. 5.2. Block Diagram of Calibration System for Tape Recorder Plus Microphone

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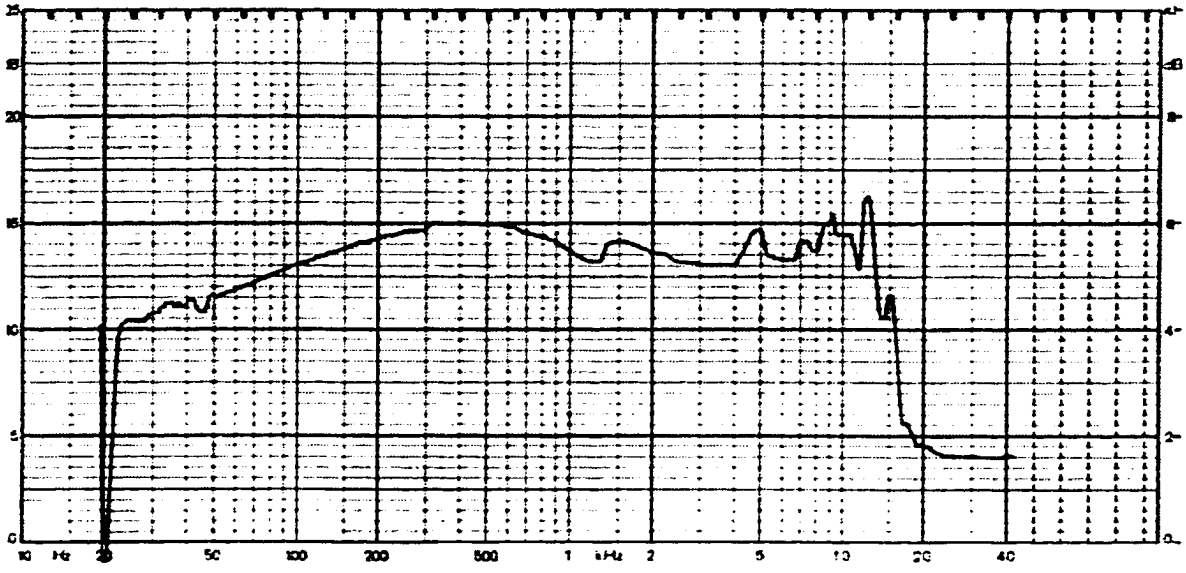


Fig. 5.3. Frequency Response of Uher Recorder Plus Electrovoice Microphone (Model 635A - Serial #8846)

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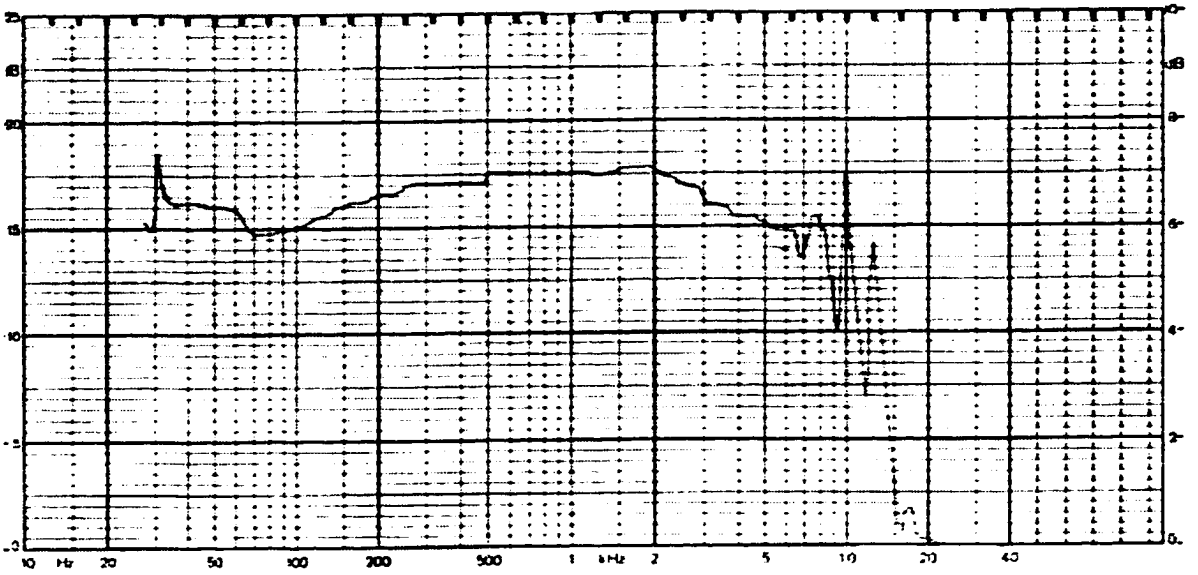


Fig. 5.4. Frequency Response of Uher Recorder Plus Electrovoice Microphone (Model 635A - Serial #8434)

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Fig. 5.5. Frequency Response of Marantz Recorder Plus Electrovoice Microphone (Model 635A - Serial #8846)

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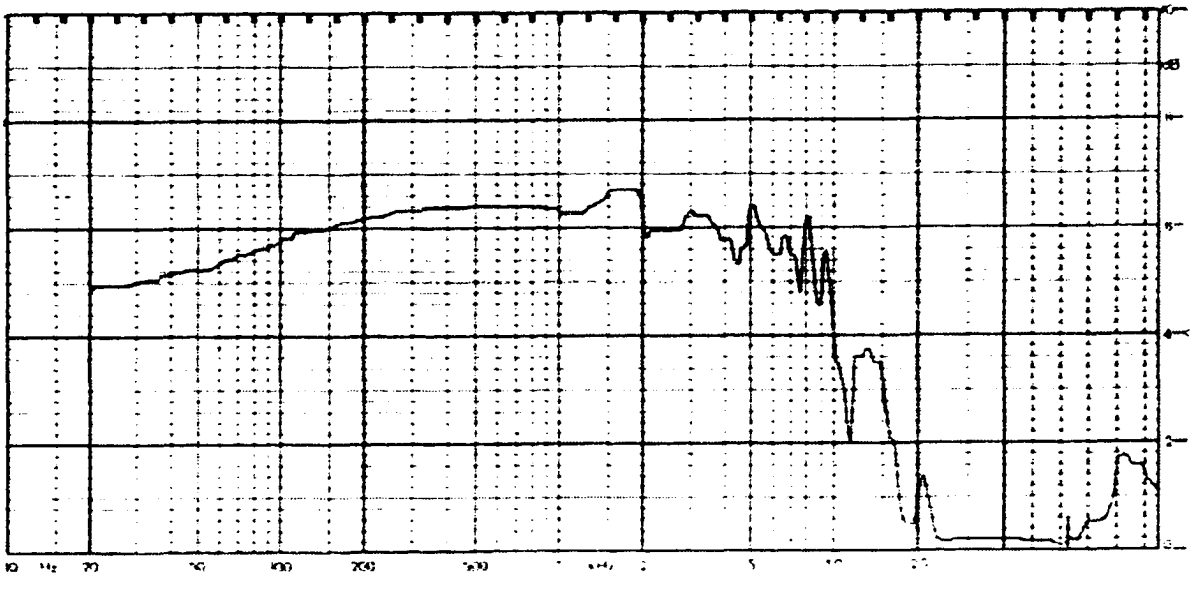


Fig. 5.6. Frequency Response of Panasonic Digital Recorder Plus Electrovoice Microphone (Model 635A - Serial #8434)

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For Presentation of Stimuli to Listeners

The Marantz portable cassette tape recorder (Model PMD430) was originally used to record the Boothroyd (1984, 1985) CVC words spoken in carrier phrases by the adults with hearing impairment. (See "Chapter Six".) It also was used to play that material for the listeners. They audited the materials individually through a set of foam-type Sennheiser earphones (Model HD414). The frequency response of the tape recorder itself was obtained using the calibration system presented in Figure 5.7. The frequency response of the tape recorder plus the left and right Sennheiser earphones was obtained using the calibration system presented in Figure 5.8. The frequency response curves are displayed in Figures 5.9 to 5.11.

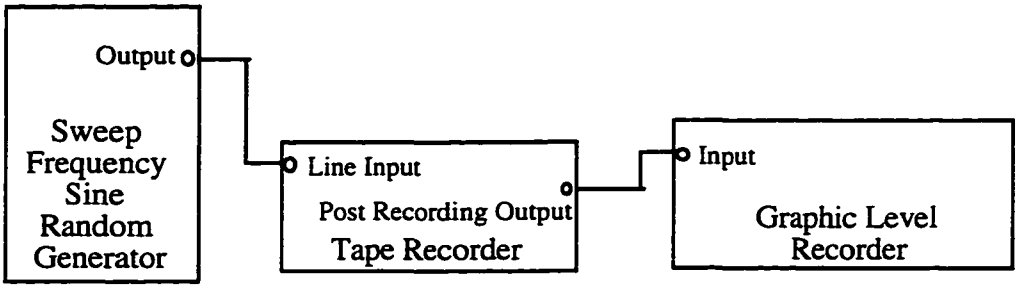


Fig. 5.7. Block Diagram of Calibration System for Marantz Tape Recorder Only

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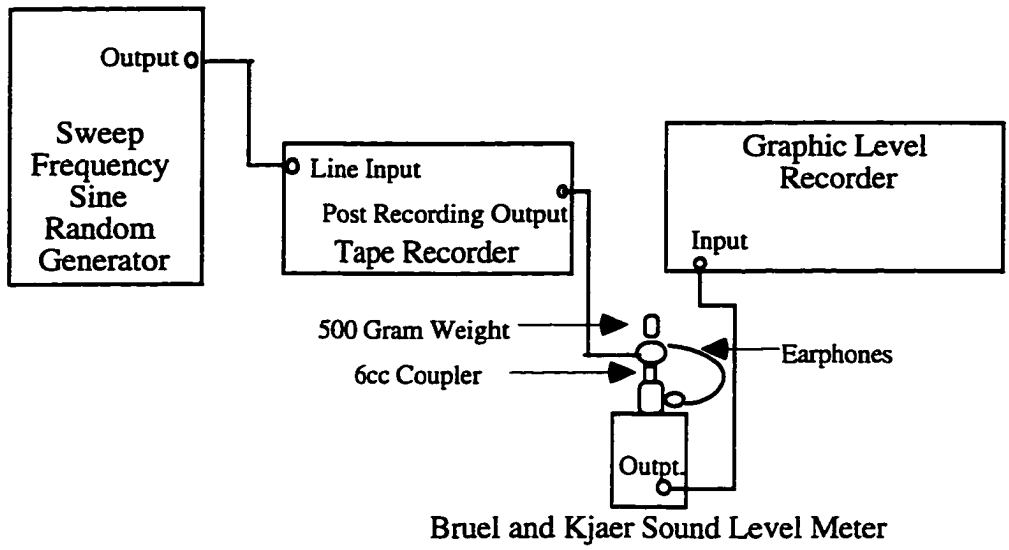


Fig. 5.8. Block Diagram of Calibration System for Marantz Tape Recorder Plus Sennheiser Earphones

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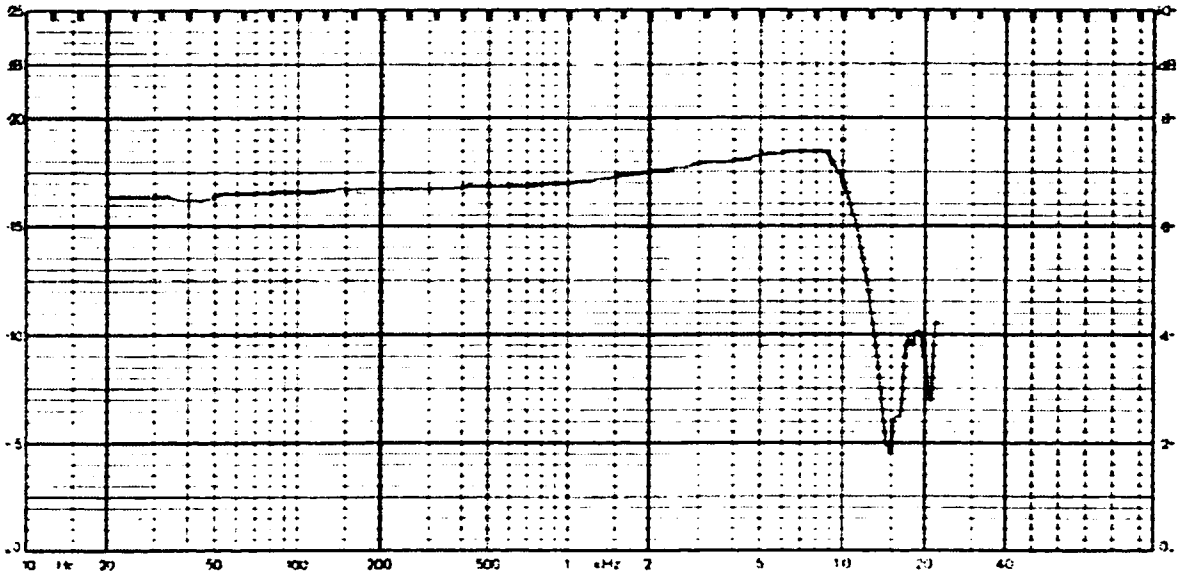


Fig. 5.9. Frequency Response of Marantz Recorder Only

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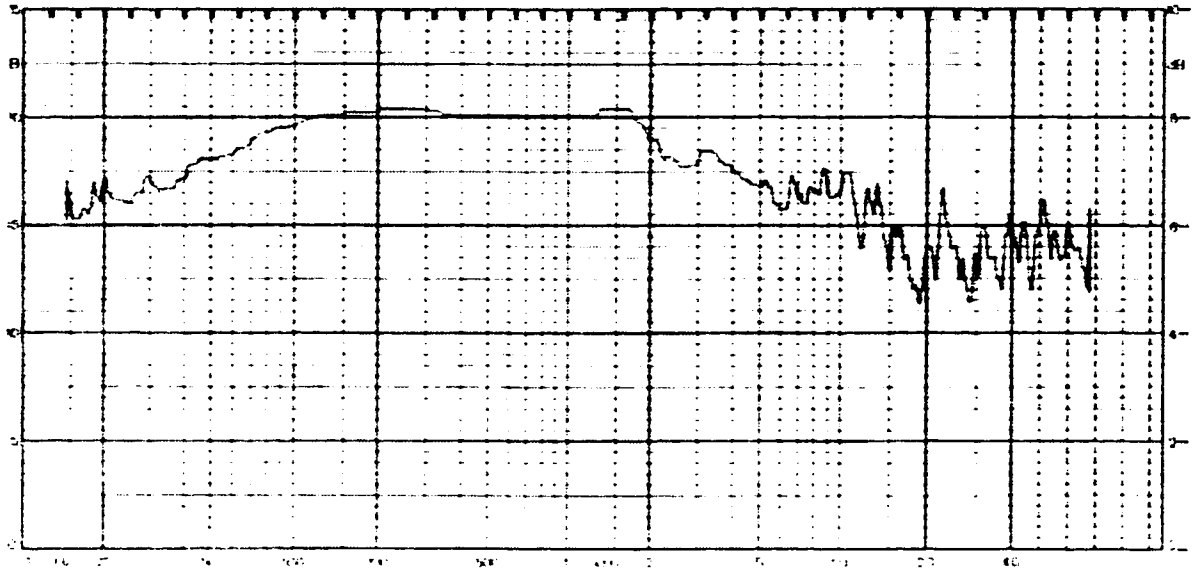


Fig. 5.10. Frequency Response of Marantz Recorder Plus Left Sennheiser Earphone

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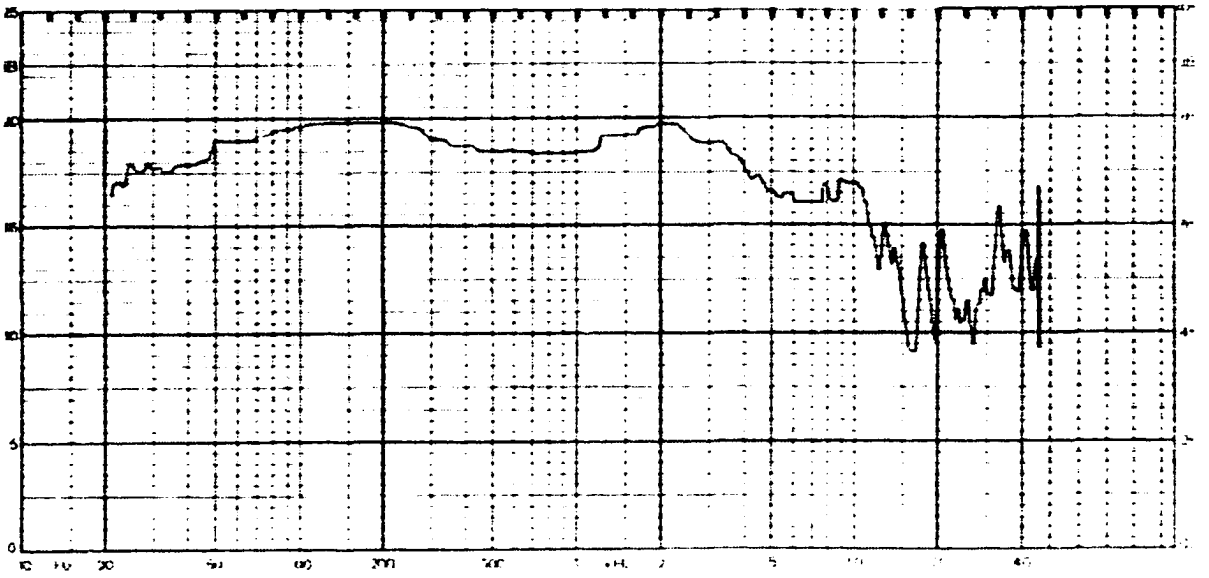


Fig. 5.11. Frequency Response of Marantz Recorder Plus Right Sennheiser Earphone

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Procedures

The procedures for all groups of subjects were of the same general format. They began with either hearing screening or formal audiological testing, for subjects with normal hearing and for subjects with hearing impairment, respectively.

Subjects then practiced jaw-opening and careful closing to a wooden tongue depressor, turned sideways and placed between the upper and lower incisors in preparation for creation of the customized bite blocks. The bite block was made and then trimmed, after the appropriate set-up time for the dental impression material used.

For speech recording, five of the children were seated in the library of the preschool they attended. The sixth child was recorded in a quiet testing room at Haskins Laboratories. All adult subjects with hearing impairment were tested in a quiet, sound-treated testing room at the school that eleven of the twelve had attended. The adult subjects with normal hearing were tested in a sound-proof booth in the laboratories at the CUNY Graduate Center. All four recording locations provided quiet testing areas ensuring good signal-to-noise ratios. The microphone was placed in a mike stand at a table so that the distance from the speaker's mouth was approximately four to five inches.

Sentences used for speech intelligibility ratings were rehearsed and then recorded by the hearing-impaired adults. Test words unknown to or mispronounced by the subjects were individually rehearsed until the subject and the experimenter agreed on the correct pronunciation. If diacritical symbols proved helpful, they were written above a difficult test word to aid memory. Order of the stimulus items was randomized as previously described.

Rehearsal of test stimulus items was given all subjects to ensure correct identification of either a picture representation of hat, heat, or hit (for children) or print (for all adults). The children rehearsed the test items several times upon presentation of pictures in random order, to be certain they understood the procedure very well. In the case of hearing-impaired adults, the test items were rehearsed until the subject and the experimenter

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agreed upon the pronunciation of each. All subjects then practiced saying the test words in the context of the carrier phrase. Order of the stimulus items was randomized as previously described.

In all cases, subjects were asked to repeat an item if 1) the subject showed disapproval of his own production, or 2) if having previously demonstrated ability to utter test items unambiguously, it was obvious to the experimenter that the subject had produced a different vowel or word.

The order in which conditions were presented to subjects was randomized across each subject in every group. As discussed previously, the order in which the stimulus items were spoken by the subjects in each condition was randomized within and across speakers in each subject group. Thus for each group of six subjects, six of the 24 possible combinations of the four word lists were paired with six of the 24 possible combinations of the four conditions of the experiment. (See Appendix B.) The six combinations chosen ensured that 1) every condition and every word list was presented in both first and last positions (although not all inner position combinations were used) and 2) that one particular word list was not always paired with one particular condition. The order of conditions and word lists in which speech was produced by each subject is listed in Table 5.4.

Sessions for adults with normal hearing included hearing and middle-ear screening, making a customized bite block, and recording the test stimuli in four conditions. Sessions typically averaged a total of two hours. A rest period was always scheduled to occur between bite-block and bite-block-plus-masking conditions, so that learning effects for speaking with a bite block could be minimized. Depending on the order of conditions for a particular subject and scheduling constraints, the sessions were divided into recordings on two consecutive days, morning and afternoon recordings of the same day, or same-day recordings separated by a rest period of one to several hours.

Sessions for adults with hearing impairment included hearing and middle-ear testing by an audiologist, making a customized bite block, recording the speech intelligibility

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Table 5.4.--Order Of Conditions And Word Lists Produced by Each Subject

Subjects	Order of Conditions	Order of Word Lists
Adults with Normal Hearing		
N1M	BXMN[1]	2134
N2F	XMNB	3124
N3M	XBNM	4123
N4F	NXBM	3412
N5M	NBXM	1234
N6M	BMNX	2413
Children with Normal Hearing		
C1F	MNXB	2143
C2M	XMBN	2341
C3F	MBNX	1243
C4M	NMXB	4123
C5M	BMXN	1234
C6F	BNXM	2134
Adults with Profound Hearing Loss		
P1M	NMXB	1342
P2F	BMXN	3142
P3M	BNMX	1432
P4M	MNBX	4312
P5F	XBMN	4231
P6M	XNBM	1423
Adults with Severe Hearing Loss		
S1M	MNXB	4123
S2M	XMBN	2341
S3F	NMBX	3421
S4M	XNMB	2431
S5F	BNXM	1243
S6F	MBXN	3241

[1] N = Normal
M = Masking
B = Bite-block
X = Bite-block plus Masking

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CVC-words-in-sentences materials, and recording the test stimuli in four conditions. Sessions typically averaged a total of three hours. As for the adults with normal hearing, a rest period was always scheduled to occur between bite-block and bite-block-plus-masking conditions, so that learning effects for speaking with a bite block could be minimized. Depending on the order of conditions for a particular subject and scheduling constraints, the sessions were divided into recordings on two consecutive days, morning and afternoon recordings of the same day, or same-day recordings separated by audiological testing or by a rest period of one to several hours.

Sessions for the children included hearing screening, making a customized bite block, recording a nursery rhyme for a speech normalcy rating, and recording the test stimuli in four conditions. Typically the sessions averaged a total of three to four hours. Because the attention span of the three- and four-year-olds was short, nearly every portion of the experimental procedure was done in separate 30-minute sessions on consecutive days. A few of the children had their hearing screened and had a customized bite block made at the same session, but all recordings of test stimuli in the four conditions were done on separate days.

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Data Analysis

Analog-to-Digital Conversion

The recorded speech signals were digitized using Haskins Laboratories' Input software and Speech Input/Output Processor (SIOP), a pulse code modulation (PCM) system (Whalen, Wiley, Rubin, and Cooper, 1990). The SIOP processor had a spectrum analyzer with a 12-bit analog-to-digital converter and a sharply tuned anti-aliasing Nyquist filter reaching a 3-dB attenuation level at 9.6 kHz. Signals were analyzed at a sampling rate of 20 kHz, using high frequency pre emphasis. The SIOP processor has a specialized filter, the high-frequency pre emphasis filter, that aids in the representation and analysis of high-frequency sounds. Because high frequencies are often difficult to measure or detect when input at their natural level, this filter boosts the amplitude of the high frequencies (before digitization) by a reliable and known amount. The pre emphasis function used with the 20-kHz sampling rate results in a response that is fairly linear up to 1 kHz and then rises exponentially above that. A complementary filter with exactly the reverse characteristics reduces the amplitudes by the same amount when the digitized signal is played out. The pre emphasis function aided the identification and segmentation of the onset of periodicity of the vowel following the aperiodic aspiration of the initial consonant /h/ and the offset of the vowel at the point of termination of periodic activity before the final /t/ consonant closure.

Segmentation Procedures

Once digitized, the CVC-words-in-sentences material, produced by the adults with hearing impairment, and the carrier phrases containing the /hVt/ stimuli, produced by all subjects, were segmented. Segmentation was done initially by means of the Haskins Laboratories' Waveform Editing and Display Program (WENDY) and later by means of the Haskins Analysis/ Display/ Experiment System (HADES), developed for use on Vax workstations. Both editors provide continuously variable cursors (head and tail markers).

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Segmentation was done by hand by the experimenter. Decisions regarding where to segment speech strings were made using both visual (observation of the waveform) and auditory (listening to the edited sample) information.

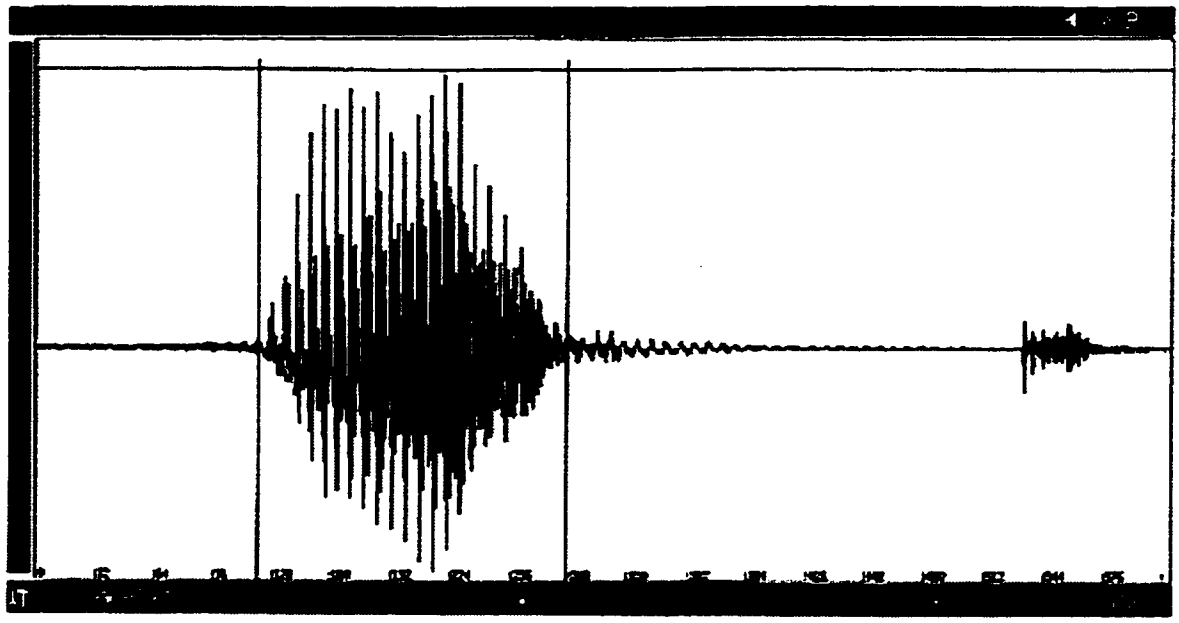
The protocol to extract a single sentence from the CVC-words-in-sentences material was simply to set the head and tail markers as close as possible to the onset of "Write" and the offset of "next" ("Write the word ___ next.") without eliminating any articulatory/acoustic information. 480 sentence files were created (12 hearing-impaired talkers x 40 sentences).

The protocol to extract the vowels from the /hVt/ words in the carrier phrase "Say hVt again" was based in most cases on identifying a place of change of excitation type. That is, the onset of periodicity of the vowel was identified following the aperiodic aspiration of the initial consonant /h/. Offset of the vowel was identified at the point of termination of periodic activity before the final /t/ consonant closure. However, there were many cases in which the offset of the vowel had to be determined using different segmentation rules. Five types of exceptions were most common: 1) periodic activity reaching minimum amplitude well before the final /t/ consonant closure (Figure 5.12), occurring primarily in productions by hearing-impaired speakers; 2) an unaspirated final /t/ closure, characteristic of many subjects with normal hearing; 3) pre-aspiration or palatalized frication between the periodic activity of the vowel and the final /t/ closure (Figures 5.13 and 5.14), occurring primarily in productions by hearing-impaired speakers; 4) use of a flap or /d/ closure instead of final /t/ (Figure 5.15), occurring primarily in productions by children and adults with normal hearing; and 5) failure to produce a final consonant resulting in coarticulation with the vowel in the first syllable of "again" (Figure 5.16), occurring primarily in bite-block conditions where subjects were not compensating fully to make consonantal closure. In the first four cases, offset of the vowel was judged to be at the point where periodic activity leveled-off or reached a minimum amplitude. In the case where there was no final consonant closure, segmentation was determined primarily by

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listening to the edited sample and by observation of the waveform when amplitude changes could augment the auditory information. 4,608 vowel files were created (24 speakers x 4 conditions x 3 vowels x 16 repetitions).

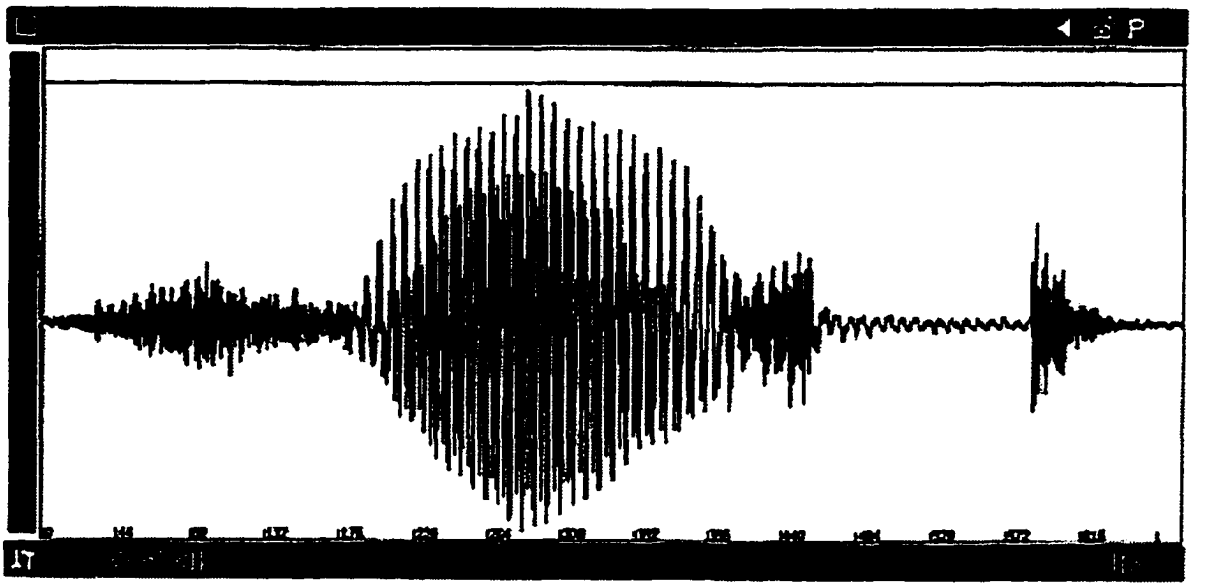
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/h. . . . . I . . . . . .t/

Fig. 5.12. Periodic Vowel Activity Reaching Minimum Amplitude Before the Final /t/ Consonant Closure in Hit

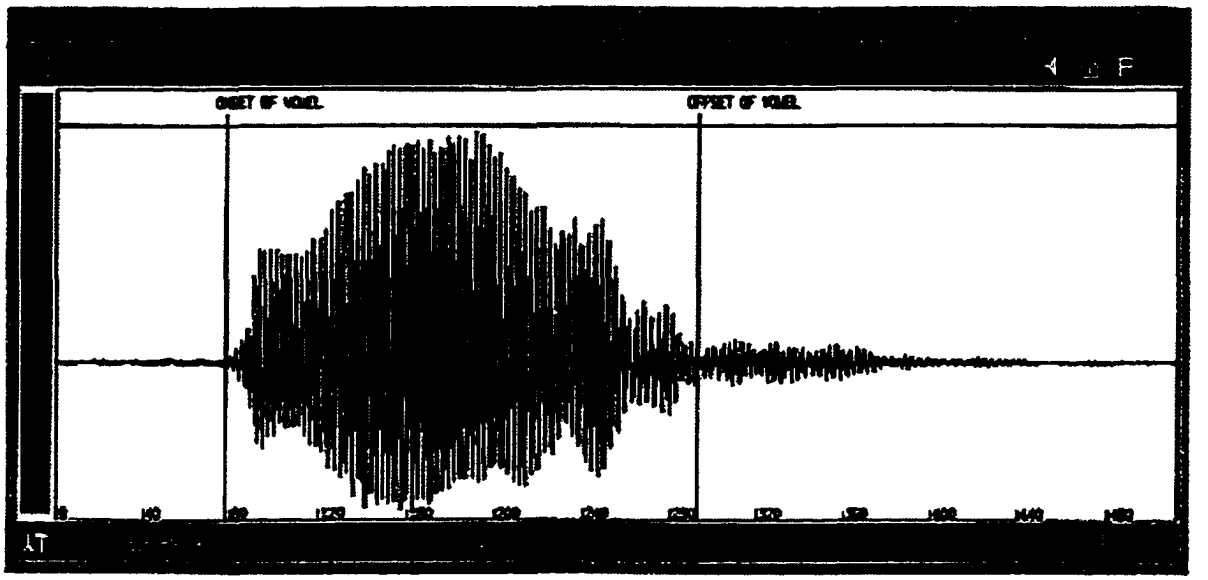
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/h. . . . . i . . . . . (pre-aspiration) . . . . . t/

Fig. 5.13. Pre-aspiration Between the Periodic Activity of the Vowel and the Final /t/ Closure in Heat

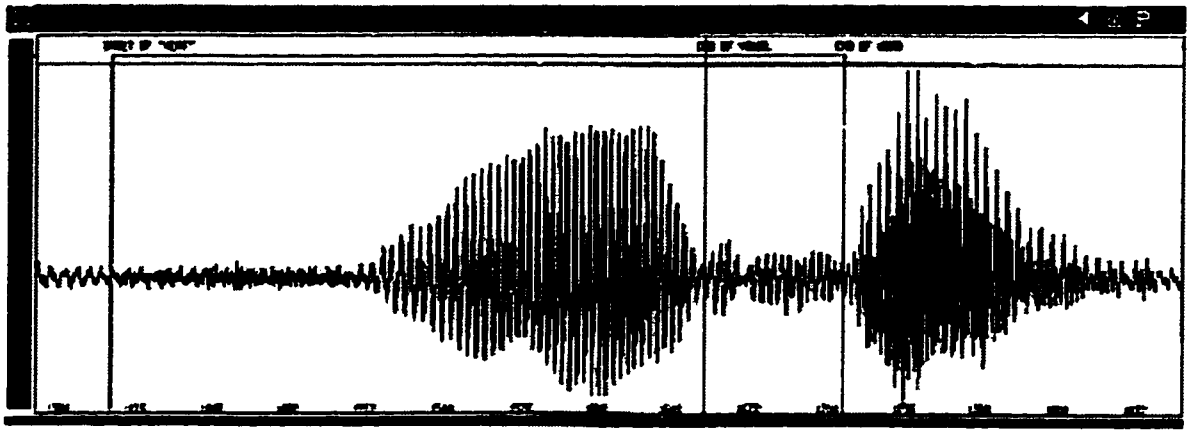
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/h . . . . . .I . . . . . (palatalized frication) . . . . . /➔ t

Fig. 5.14. Palatalized Frication Between the Periodic Activity of the Vowel and the Final /t/ Closure in Hit

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/h . . . . . .i . . . . . .də . . . . . .gɛn/

Fig. 5.15. Use of a Flap or /d/ Closure Instead of Final /t/ Between "heat a-" of "heat again"

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/s . . . . . .ei . . . . . h . . . . i . . . . .ə . . . . .g . . . . . ɛ . . . n/

Fig. 5.16. Failure to Produce a Final Consonant /t/ Resulting in Coarticulation of the Vowel /i/ in Heat with the Vowel in the First Syllable of Again for the Phrase "Say heat again."

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Acoustic Analysis

Formant frequency, bandwidth, and RMS amplitude were estimated using a Linear Predictive Coding (LPC) analysis program owned by Haskins Laboratories, ILS Signal Analysis, produced by Signal Technology, Inc. The LPC program used the autocorrelation method to calculate reflection coefficients on a frame by frame basis. Then a root solving command was applied to enhance resonance calculations. It calculated spectral peaks by retrieving the reflection coefficients from the analysis file and computing the coefficients of the autoregressive polynomial. The polynomial was then solved to obtain the complex roots which are transformed to resonance frequencies. Fundamental frequency was determined based upon a modified cepstral processing technique.

While the sampling rate was set to 20 kHz, other user-controlled parameters were chosen depending on the source characteristics of each subject's data set. The length of the analysis window was set to 20 milliseconds with frame size set to 10 milliseconds, resulting in a 50% overlap as the analysis window moved from frame to frame. The number of predictor coefficients varied from 12 to 24 and were chosen for "best fit" to the source characteristics of each subject. In general, choosing fewer coefficients led to estimates that "missed" formants and choosing more coefficients led to over-identification of spectral peaks. However, for any one subject, movement in either one direction or the other was frequently shown to enhance accurate identification of appropriate and stable formant resonances.

A Haskins Laboratories-developed software package, ANAL, was also used. It served as an interface between the user and the ILS LPC software. ANAL simplified some of the tedious requirements of ILS, including file-naming conventions and use of syntactically well-formed ILS commands. It also created a text file containing the most commonly needed analysis results from the more detailed ILS analysis file. A combination of command procedures was used from each, taking advantage of the short cuts of ANAL, while not losing the greater capacity and flexibility of the ILS package itself.

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As stated earlier, formant frequencies were derived from LPC analysis using a 12- to 24-pole autoregressive filter at the vowel midpoint. Further checks were done using Fast Fourier Transform cross-sections and numerical values of bandwidths and formant frequencies derived by LPC analysis. Cross-sections were generated for the frame where formant frequency values were obtained from LPC analysis and were visually checked to compare prominent harmonics in the spectrum to the obtained LPC formant values. Bandwidths over which formants were resolved served to help determine whether the analysis program was designating individual harmonics as formants or, alternatively, if it was resolving formant resonances over too wide a range. Formant values were also visually checked across all frames through the entire vowel token to ascertain consistency of resonance measures. For some tokens, the LPC analysis simply could not resolve any stable resonances within the frames selected for measurement (see below). If formant measures were not resolved for a particular token, no measures of fundamental frequency or RMS amplitude were used from it either. Furthermore, based on information from a study of the bandwidth of vowel formants by Bogert (1953), a measurement protocol was selected that required formant values with bandwidths of less than 50 Hz and greater than 500 Hz to be rejected.

Samples of formant frequencies obtained through LPC analysis were independently verified by comparison to wideband spectrograms (Discrete Fourier Transforms) and DFT cross-sectional displays using HADES (described in "Segmentation Procedures"). The first four tokens of each of the three vowels in each of the four conditions were analyzed for each subject via cross-sections of wideband spectrograms. This procedure yielded 48 comparisons per subject (from a total of 192 tokens per subject). The information gained in this manner was sometimes used to guide selection of LPC parameters and was always used to verify the accuracy of LPC analysis. Tokens were included in the data set only when corresponding values were obtained by each method.

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In only one instance were measures obtained through DFT wideband spectrograms and DFT cross-sectional displays alone. An adult with severe hearing loss, S5F, produced a voice quality in the Normal condition for hat that was harsh and nasal, yielding four resonance peaks in that condition only. The second peak was believed to be a possible tracheal resonance. LPC analysis could not detect the first formant, clearly visible by eye, but greatly reduced in amplitude. Consequently, Hades DFT measures were used for the entire normal /ae/ condition. This was the only instance in this dissertation in which DFT measures were used rather than LPC-derived/DFT-verified values.

If one formant measure was resolved over an acceptable bandwidth and compared reliably with FFT cross-sections and DFT measures, but the other formant measure was not resolved or did not meet any one of those standards, neither value was used. The configuration of the entire vocal tract affects each resonant frequency and the first and second formant measures are not truly independent, so the failure to reliably resolve one formant was judged to require the rejection of the other. Criterion for inclusion of a condition was a minimum of eight tokens in which both F1 and F2 measures were obtained.

All measurements derived by the ILS analysis were selected from the frame at, or plus/minus one frame from, vowel center. Measurements at the onset of the vowel were not practical given the gradual onset of phonation after initial consonant /h/. Obtaining measurements at vowel center ensured that formants were as near target and steady-state as possible and had the effect, without the rule, of obtaining values where peak vowel amplitude was usually greatest. Furthermore, measurements at this location also ensured very conservative judgments of failure to compensate for the presence of a bite block, masking noise, or both.

Fundamental frequency measures were obtained reliably through ILS analysis for the adults with normal hearing and for some of the adults with hearing impairment. Reliable measures were not always realized for the four-year-olds and for hearing-impaired

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adults with harsh or breathy vocal quality. In those cases the investigator measured average pitch directly from the waveform over five glottal pulses at the center of the vowel, using the WENDY editing and display program (described in "Segmentation Procedures").

Statistical Analyses of Data

In Chapter Seven through Chapter Ten, results of formant measurements are presented for each of the subject groups, respectively. Group F2, F1, F2 standard deviation, and F1 standard deviation data were submitted separately for each vowel, to a one-way repeated measures ANOVA (by Condition) for the adults with normal hearing, the children, and the adults with severe hearing loss, because data were missing for individuals within these groups. For consistency, the same analysis was performed on the data from the adults with profound hearing loss, but in addition, because the data from all of these individuals were available, data were also submitted to a two-way repeated measures ANOVA (Condition by Vowel).

Chapter Seven through Chapter Ten also present analyses of formant measurements for every individual subject. F2 and F1 measurements from each individual's tokens in each condition were submitted to three-way ANOVAs (Bite Block x Masking x Vowel) for each subject separately, treating each token from each individual as a sample. Two-way ANOVAs were also performed for the standard deviations of F2 and F1 for each subject separately, using the twelve standard deviation values from three vowels in four conditions as the raw data. Three-way ANOVAs could not be performed because each cell had only one value. Thus the analyses were collapsed across one dimension, to perform two-way ANOVAs (Bite Block x Masking; Bite Block x Vowel; Masking x Vowel).

In Chapter Eleven, mean RMS amplitude measures in decibels and mean fundamental frequency values in Hertz (and the standard deviation values for each) for every vowel in every condition for each subject (for whom there were data) were submitted to two-way repeated measures ANOVAs (Condition x Group).

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CHAPTER SIX

INTRODUCTION TO RESULTS CHAPTERS AND RESULTS FROM SPEECH INTELLIGIBILITY MEASURES OF THE ADULTS WITH HEARING LOSS

Introduction to Results Chapters

Every vowel token produced by every subject in each of the four subject groups was submitted to acoustic analysis in which the following four physical parameters were measured:

(1) second formant frequency
(2) first formant frequency
(3) fundamental frequency
(4) and intensity.

The purpose of this analysis was to address the three primary theoretical questions: 1) To what degree do adults with normal hearing compensate for a bite block and what is the role of auditory feedback in this compensation? 2) To what degree do children with normal hearing compensate for a bite block and what is the role of auditory feedback in this compensation? and 3) Are auditory representations critical to the specification of articulatory reorganization for a bite block? Second and first formant frequency measurements of vowels produced normally (for adults with hearing loss, this meant while using their usual hearing aid amplification) were compared both to the formant measurements of vowels produced with a bite block alone and to the formant measurements of vowels produced with a bite block while subjects listened to masking noise (for the adults with hearing loss, this also meant with hearing aids removed). These measurements provided information as to whether or not speakers compensated for a bite block when they heard themselves speak and when they did not. The condition of vowel production with masking noise served to allow the comparison of second and first formant frequencies from

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it with those from the normal condition in order to account for any effects on vowel production of the removal of auditory feedback alone.

The second and first formant measurements provided two tests of whether auditory feedback affects performance of compensatory vowel production. While the configuration of the entire vocal tract affects each resonant frequency and the second and first formant measurements are not truly independent, for the purposes of observation and analysis they were considered such here.

Chapters 7, 8, 9 and 10 present the results of acoustic analysis related to second and first formant frequency measurements for each of the four subject groups, respectively. In these chapters the actual formant values are presented for each group together with percent-change of formant frequency measurements of test conditions from the normal condition. The standard deviation values of these measurements were also used as raw data.

The measurements of fundamental frequency and intensity served as indicators of the validity of observed formant frequency changes from condition to condition. That is, it was necessary to rule out the effects that fundamental frequency and intensity may have had on formant frequencies. For example, if a condition, such as presentation of masking noise, systematically elicited louder phonation at a higher fundamental frequency, absolute formant frequency values might have been altered as a result of voice source changes rather than articulatory adjustments. Fundamental frequency and intensity values of each vowel token from all four subject groups were combined and examined together in a separate chapter, Chapter 11.

It was also of interest to know if subjects benefited from practice as they proceeded through bite-block conditions. Presentation order of the four conditions (Normal, Bite-Block, Bite-Block-Plus-Masking, and Masking) was counterbalanced within and across all subject groups, but learning whether subjects benefited from practice effects within

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condition was also desired. Selected data from each of the four subject groups were also combined and examined together to address this question in Chapter 11.

Finally, it was also considered desirable to have a quantifiable measure of the speech intelligibility of the adults with hearing loss in order to describe the subjects accurately and to offer possible explanations for acoustic evidence obtained. Those results are presented below.

Results from Speech Intelligibility Measures of the Adults with Hearing Loss

A separate study of speech intelligibility measures of the speech of the adults with hearing loss was conducted to provide basic descriptions of these subjects' production skills. It is well known that the intelligibility of individuals with severe and profound hearing loss may vary widely. Intelligibility measures were conducted to provide carefully documented speech profiles for each hearing-impaired subject in the event that ability to compensate for a bite block might be correlated not only with the amount of residual hearing, but also with speech production skill.

Subjects

Speakers

The six adults with profound hearing loss and the six adults with severe hearing loss, described in "Subjects" of the "Methods" chapter served as the talkers in this intelligibility study.

Listeners

Fifteen inexperienced listeners participated in this study. Listeners were considered to be inexperienced if they reported no more than incidental or limited experience listening to the speech of individuals with hearing impairment. Eight reported having no experience, and five reported only incidental contact with hearing-impaired speakers. Two reported

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having either friends or relatives with hearing impairment; their percent-correct word, consonant, and vowel identification scores were similar to those of the other 13 listeners when listening to the recordings of the hearing-impaired subjects, so their data were included with that from the rest of the group.

All listeners were adult native speakers of American English with no known hearing impairment. All were graduate students in either speech-language pathology or audiology at St. John's University in (Jamaica, Queens) New York City.

Stimuli

Before recording stimuli in test conditions, the adults with hearing loss recorded sentences used for speech intelligibility measures. Boothroyd's (1984,1985) CVC word lists were used for this purpose. Boothroyd demonstrated that such lists can provide measures of speech production intelligibility that are context-free, essentially independent of listener experience, and reasonably predictive of a person's intelligibility in a more natural communicative situation. These lists provide for the testing of open-set recognition of phonemes in monosyllabic words. They are composed of 20 CVC words in the context "Write the word _____ next." Each list contains two examples of each of 30 phonemes. The 20-word lists are constructed from two ten-word lists taken from Boothroyd's (1984) fifteen isophonemic word lists (see Table 6.1). Only eight of Boothroyd's fifteen lists were used in this study (note that "List #5" was not used).

Table 6.1.--Isophonemic Word Lists (Boothroyd, 1984)

List #1	List #2	List #3	List #4	List #6	List #7	List #8	List #9
ship	fish	thug	fun	fill	badge	bath	hush
rug	duck	witch	will	catch	hutch	hum	gas
fan	patch	teak	vat	thumb	kill	dig	thin
cheek	cheese	wrap	shape	heap	thighs	five	fake
haze	race	vice	wreath	wise	wave	ways	chime
dice	hive	jail	hide	rave	reap	reach	weave
both	bone	hen	guess	got	foam	joke	jet
well	wedge	shows	comb	shown	goose	noose	rob
jot	log	food	choose	bed	not	pot	dope
move	tomb	bomb	job	juice	shed	shell	lose

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Table 6.2.--Speech Intelligibility Word Lists

List One (#2 + #4)	List Two (#1 + #3)
Write the word fish next.	Write the word ship next.
Write the word duck next.	Write the word rug next.
Write the word patch next.	Write the word fan next.
Write the word cheese next.	Write the word cheek next.
Write the word race next.	Write the word haze next.
Write the word hive next.	Write the word dice next.
Write the word bone next.	Write the word both next.
Write the word wedge next.	Write the word well next.
Write the word log next.	Write the word jot next.
Write the word tomb next.	Write the word move next.
Write the word fun next.	Write the word thug next.
Write the word will next.	Write the word witch next.
Write the word vat next.	Write the word teak next.
Write the word shape next.	Write the word wrap next.
Write the word wreath next.	Write the word vice next.
Write the word hide next.	Write the word jail next.
Write the word guess next.	Write the word hen next.
Write the word comb next.	Write the word shows next.
Write the word choose next.	Write the word food next.
Write the word job next.	Write the word bomb next.

List Three (#6 + #8)	List Four (#7 + #9)
Write the word fill next.	Write the word badge next.
Write the word catch next.	Write the word hutch next.
Write the word thumb next.	Write the word kill next.
Write the word heap next.	Write the word thighs next.
Write the word wise next.	Write the word wave next.
Write the word rave next.	Write the word reap next.
Write the word got next.	Write the word foam next.
Write the word shown next.	Write the word goose next.
Write the word bed next.	Write the word not next.
Write the word juice next.	Write the word shed next.
Write the word bath next.	Write the word hush next.
Write the word hum next.	Write the word gas next.
Write the word dig next.	Write the word thin next.
Write the word five next.	Write the word fake next.
Write the word ways next.	Write the word chime next.
Write the word reach next.	Write the word weave next.
Write the word joke next.	Write the word jet next.
Write the word noose next.	Write the word rob next.
Write the word pot next.	Write the word dope next.
Write the word shell next.	Write the word lose next.

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Table 6.2 illustrates that pairs of these lists were combined to create the 20-word lists. Each hearing-impaired subject recorded two of four possible 20-word lists.

Each sentence spoken by each speaker was digitized at a sampling rate of 20kHz, using analog-to-digital software at Haskins Laboratories, and saved as an individual file, labeled by speaker and by whether it came from the first or the second list produced by that speaker. These files were then put in random order, within list, and spaced with time intervals of one second between repetitions and five seconds between sentences, using Haskins Laboratories' in-house software, SEQ Version 3.0. The SEQ program creates a PCM sequence file to be used with PCM output programs. All items within each list were put in random order three times, resulting in three versions of every list from every speaker. These versions were given color names for use in subsequent listening tape creation and labeling, and listener grouping. The lists were then put in analog form, using Haskins Laboratories' Output software, and re-recorded with the same tape recorder used at the original recording session. Three sets of tapes were made, each with a unique order of presentation (see Table 6.3).

Initially, an order of talkers was developed that randomized those talkers with respect to age, sex and hearing loss. Thereafter, each tape set presented speakers in precisely that same order. One list was presented from each of the 12 speakers. Then a second list from each of those 12 speakers was presented in the reverse order. In this way, Speaker S2M, whose first list was presented first to each listener when they had no practice, became the last speaker, whose second list was presented to listeners when they had the most practice. The presentation order of the two lists from each speaker was also randomized three times.[1]

[1]It will be remembered from "Subjects" in the "Methods" chapter that a seventh adult with profound hearing impairment participated, but did not ultimately serve, as a subject for this study. He also recorded two 20-word lists that were audited by the 15 listeners. Because he did not serve as a subject, discussions of his data are not included in text, tables or figures here. His lists were recorded and audited between those of P2F and P4M in each of the three sets of tapes created.

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Table 6.3.--Speech Intelligibility Listening Tapes: Order of Presentation

Tape Set 1: Green (five listeners) Order of Presentation			Tape Set 2: Orange (five listeners) Order of Presentation			Tape Set 3: Purple (five listeners) Order of Presentation		
Speaker	List	Random Order	Speaker	List	Random Order	Speaker	List	Random Order
S2M	First	Green	S2M	First	Orange	S2M	Second	Purple
S1M	First	Green	S1M	First	Orange	S1M	Second	Purple
S6F	Second	Green	S6F	First	Orange	S6F	First	Purple
P3M	Second	Green	P3M	First	Orange	P3M	First	Purple
P6M	First	Green	P6M	Second	Orange	P6M	Second	Purple
S3F	Second	Green	S3F	First	Orange	S3F	Second	Purple
P5F	Second	Green	P5F	First	Orange	P5F	First	Purple
P2F	First	Green	P2F	First	Orange	P2F	Second	Purple
P4M	First	Green	P4M	First	Orange	P4M	Second	Purple
S4M	Second	Green	S4M	First	Orange	S4M	Second	Purple
S5F	First	Green	S5F	Second	Orange	S5F	Second	Purple
P1M	Second	Green	P1M	First	Orange	P1M	First	Purple
P1M	First	Green	P1M	Second	Orange	P1M	Second	Purple
S5F	Second	Green	S5F	First	Orange	S5F	First	Purple
S4M	First	Green	S4M	Second	Orange	S4M	First	Purple
P4M	Second	Green	P4M	Second	Orange	P4M	First	Purple
P2F	Second	Green	P2F	Second	Orange	P2F	First	Purple
P5F	First	Green	P5F	Second	Orange	P5F	Second	Purple
S3F	First	Green	S3F	Second	Orange	S3F	First	Purple
P6M	Second	Green	P6M	First	Orange	P6M	First	Purple
P3M	First	Green	P3M	Second	Orange	P3M	Second	Purple
S6F	First	Green	S6F	Second	Orange	S6F	Second	Purple
S1M	Second	Green	S1M	Second	Orange	S1M	First	Purple
S2M	Second	Green	S2M	Second	Orange	S2M	First	Purple

Procedures

Listeners were grouped by color name, but tapes were played to individual listeners who, during auditing, were fitted with headphones. The tapes were played on the same tape recorder used for the original speech recording. Following Boothroyd (1985), for each list listeners were given a sheet of paper containing the carrier phrase and a space in which to write the word they heard. Each sentence was heard twice and listeners then wrote the word they heard. Listeners were told that they would hear one-syllable words in the sentence "Write the word _____ next," and that they would hear only one speaker

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within each list. They were instructed to guess if they were not sure of an item. They were also instructed not to rewind the tape to listen to any sentence and its repetition more than once, but that they could pause when necessary. Feedback on their performance was withheld. This resulted in a listening requirement of approximately four to five minutes per list, or two hours total (12 speakers x 5 minutes x 2 lists = 120 minutes). Listeners audited tapes independently at an individual listening station. Each set of tapes consisted of eight numbered and color-coded cassettes. Each cassette contained three lists, requiring approximately 15 minutes of listening. Listeners completed tapes at their own pace over several days.

While the four original Boothroyd lists were repeated several times, listeners' scores did not reveal learning effects. That is, the random presentation of lists and words within lists, and the movement from one speaker to another appeared to minimize any learning of the word lists. In addition, such effects were balanced to some extent by having the first speaker of the first list be the last speaker of the last list.

The responses were recorded in three ways: 1) number of whole words correctly perceived, 2) number of constituent consonants correctly perceived, and 3) number of constituent vowels correctly perceived. Thus the word score for each speaker was based on 40 words, the consonant score on 80 consonants, and the vowel score on 40 vowels. In all, listeners made 600 word judgments (2 lists x 20 words x 1 talker x 15 listeners) and 1800 phoneme judgments (2 lists x 60 phonemes x 1 talker x 15 listeners) per speaker, providing the raw data for analysis.

Results

As stated earlier, the order in which the lists were produced was noted, in the event that the second list was produced more clearly than the first by virtue of speaker practice. Table 6.4 presents results for each speaker for the first list and for the second list they produced, and an average percentage score for both lists combined. An effect of speaker

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Table 6.4.--Speech Intelligibility of Speakers with Hearing Impairment

Speaker	% Words Correctly Understood by Listeners			% Consonants Correctly Understood by Listeners			% Vowels Correctly Understood by Listeners		
	1st List	2nd List	Combined Lists	1st List	2nd List	Combined Lists	1st List	2nd List	Combined Lists
S1M	81	80	81	88	88	88	92	95	94
S2M	40	35	38	56	56	56	76	76	76
S3F	49	46	47	72	74	73	78	81	79
S4M	80	78	79	91	87	89	97	94	95
S5F	65	64	65	79	78	79	90	95	93
S6F	71	70	71	84	86	85	89	90	89
P1M	14	19	16	42	43	42	29	32	31
P2F	21	25	23	53	61	57	37	47	42
P3M	22	27	25	47	50	48	61	56	60
P4M	24	30	27	44	53	48	60	58	59
P5F	43	39	41	68	61	65	64	57	62
P6M	43	49	46	69	67	68	65	71	68

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practice was not tested for significance, but was not apparent from the tabular presentation of data.

Figure 6.1 presents graphically the average percentage scores from the "combined lists" columns of Table 6.4. The speakers are presented in order of increasing average hearing loss. Speech intelligibility generally decreased as hearing loss increased, with some exceptions. Subject S2M, an adult with a borderline severe-to-profound hearing loss, received speech intelligibility scores that were lower than those of two subjects with profound hearing losses, P5F and P6M. Listeners usually perceived vowels more accurately than consonants. Of course, both consonant and vowel scores were always higher than word scores, because listeners often perceived part of a word correctly, but failed to understand the word itself.

The speech intelligibility measures were conducted as only one component of this larger investigation, for the purposes of providing basic descriptions of the subjects' speech production skills and offering possible explanations for the acoustic evidence that follows in the subsequent results chapters. Further analysis will be conducted with this speech intelligibility data, as a study in its own right, but will not be discussed further here.

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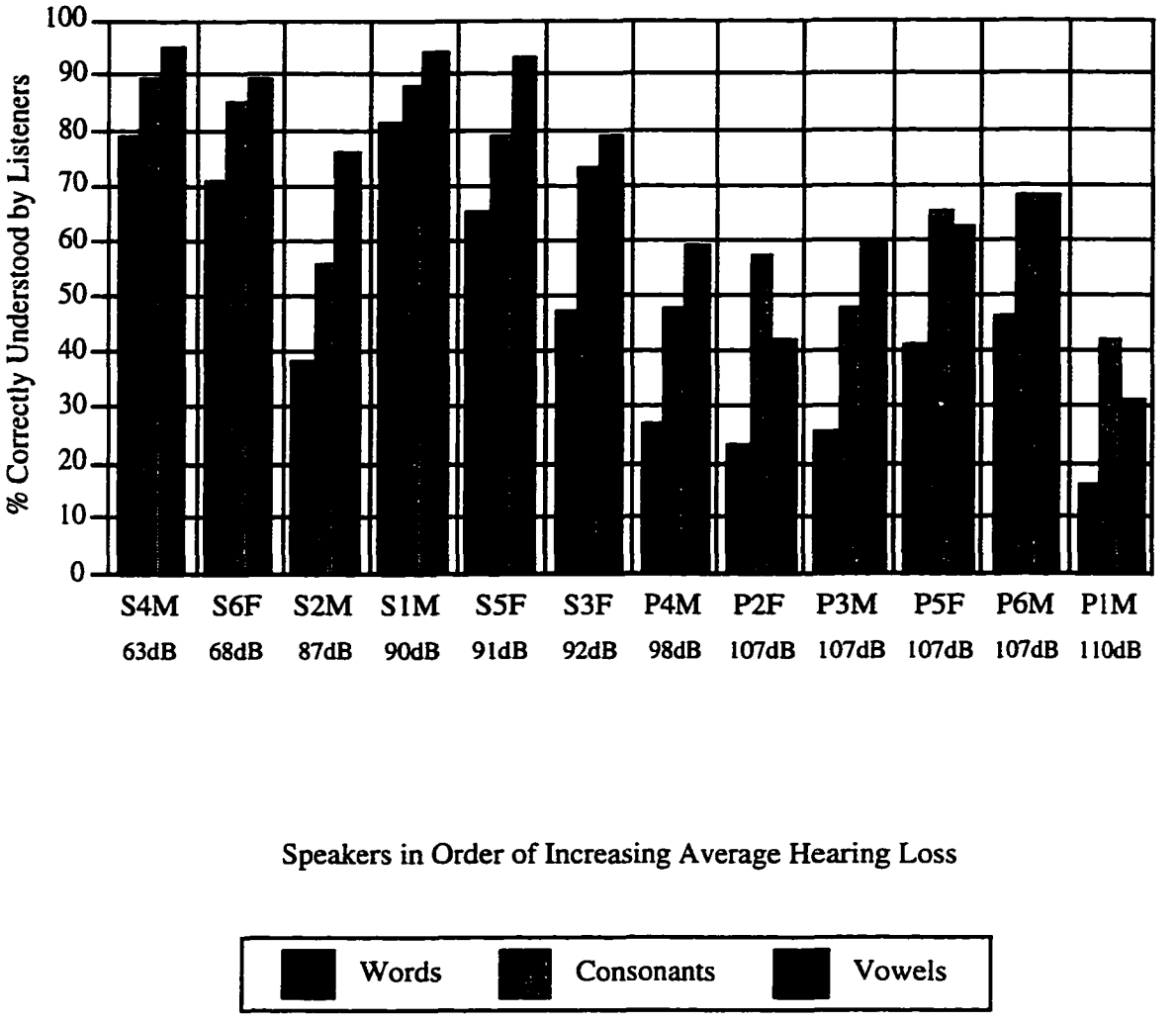


Fig. 6.1. Speech Intelligibility of Speakers with Hearing Impairment

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CHAPTER SEVEN

RESULTS: ADULTS WITH NORMAL HEARING

The application of this experiment to the group of six adults with normal hearing tested the first hypothesis of this dissertation: Adults with normal hearing compensate completely for a bite block and auditory feedback plays a role in this compensation.

Acoustic Analysis of Vowels Produced in Four Conditions: Measures of Articulatory Compensation

Group Data

Results were first examined using data collapsed across these six subjects in order to observe general behavioral patterns exhibited by the group. While the absolute formant frequency values were used for statistical tests, and are recorded in Table 7.1a-c that follows (N/A indicates missing data), they were not displayed in figures. It was not possible to compare visually the magnitude of the test condition effects using the absolute formant measurements in Hertz of each subject. It is well known that the actual resonant frequencies of vowel formants vary considerably between men and women and among individuals of varying body sizes and vocal tract configurations. Therefore, for figure presentations, in this and subsequent results chapters, percent change in formant frequency from normal to test conditions was used to illustrate changes in each of the second and first formants.

Percent change was calculated for each subject individually as ((Mean F2 for Any One Test Condition - Mean F2 for the Normal Condition) / Mean F2 for the Normal Condition) x 100 and ((Mean F1 for Any One Test Condition - Mean F1 for the Normal Condition) / Mean F1 for the Normal Condition) x 100.

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Table 7.1a.--Group Means, % Change, and Standard Deviations of F2 and F1 of Heat for Adults with Normal Hearing

Subject	Sex	Condition	Vowel	Mean F2	%Ch in F2	Mean F1	%Ch in F1	F2 SD	F1 SD
N1M	Male	Normal	heat	2345.50	***	243.33	***	24.12	8.53
N2F	Female	Normal	heat	2820.07	***	328.20	***	46.93	35.93
N3M	Male	Normal	heat	2368.38	***	242.88	***	73.76	11.66
N4F	Female	Normal	heat	2906.50	***	316.81	***	35.08	21.89
N5M	Male	Normal	heat	N/A	N/A	N/A	N/A	N/A	N/A
N6M	Male	Normal	heat	2343.31	***	271.00	***	45.71	13.98
Group Means Per Condition				2556.75	***	280.44	***	45.12	18.40
N1M	Male	Bite-Block	heat	2350.86	0.23	262.71	7.96	26.08	8.81
N2F	Female	Bite-Block	heat	2778.85	-1.46	305.15	-7.02	59.09	17.55
N3M	Male	Bite-Block	heat	2297.06	-3.01	259.38	6.79	29.36	17.97
N4F	Female	Bite-Block	heat	2848.81	-1.98	376.25	18.76	147.28	17.08
N5M	Male	Bite-Block	heat	N/A	N/A	N/A	N/A	N/A	N/A
N6M	Male	Bite-Block	heat	2200.25	-6.11	299.44	10.49	31.00	14.77
Group Means Per Condition				2495.17	-2.47	300.59	7.40	58.56	15.24
N1M	Male	Bite-Bl&Msknq	heat	2261.39	-3.59	269.39	10.71	59.80	6.50
N2F	Female	Bite-Bl&Msknq	heat	2635.07	-6.56	332.57	1.33	111.79	28.25
N3M	Male	Bite-Bl&Msknq	heat	2273.56	-4.00	293.13	20.69	48.94	23.91
N4F	Female	Bite-Bl&Msknq	heat	2784.80	-4.19	318.20	0.44	66.38	49.91
N5M	Male	Bite-Bl&Msknq	heat	N/A	N/A	N/A	N/A	N/A	N/A
N6M	Male	Bite-Bl&Msknq	heat	2127.93	-9.19	322.93	19.16	46.06	11.87
Group Means Per Condition				2416.55	-5.51	307.24	10.47	66.59	24.09
N1M	Male	Masking	heat	2299.18	-1.97	256.36	5.36	35.54	8.82
N2F	Female	Masking	heat	2808.06	-0.43	370.75	12.96	51.68	24.85
N3M	Male	Masking	heat	2282.13	-3.64	273.93	12.79	47.06	21.03
N4F	Female	Masking	heat	2863.27	-1.49	368.33	16.26	79.48	26.61
N5M	Male	Masking	heat	N/A	N/A	N/A	N/A	N/A	N/A
N6M	Male	Masking	heat	2227.38	-4.95	304.94	12.52	31.31	16.35
Group Means Per Condition				2496.00	-2.50	314.86	11.98	49.02	19.53

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Table 7.1b.--Group Means, % Change, and Standard Deviations of F2 and F1 of Hit for Adults with Normal Hearing

Subject	Sex	Condition	Vowel	Mean F2	%Ch in F2	Mean F1	%Ch in F1	F2 SD	F1 SD
N1M	Male	Normal	hit	1972.25	***	444.88	***	51.38	14.35
N2F	Female	Normal	hit	N/A	N/A	N/A	N/A	N/A	N/A
N3M	Male	Normal	hit	1949.56	***	364.00	***	42.15	41.48
N4F	Female	Normal	hit	2283.88	***	476.38	***	90.97	52.11
N5M	Male	Normal	hit	1910.73	***	407.67	***	55.35	17.47
N6M	Male	Normal	hit	2075.69	***	421.50	***	92.64	34.58
Group Means Per Condition				2038.42	***	422.88	***	66.50	32.00
N1M	Male	Bite-Block	hit	2026.00	2.73	461.50	3.74	27.77	25.87
N2F	Female	Bite-Block	hit	N/A	N/A	N/A	N/A	N/A	N/A
N3M	Male	Bite-Block	hit	1958.06	0.44	395.50	8.65	39.92	36.41
N4F	Female	Bite-Block	hit	2117.31	-7.29	491.75	3.23	55.21	36.69
N5M	Male	Bite-Block	hit	1900.81	-0.52	429.81	5.43	85.94	14.94
N6M	Male	Bite-Block	hit	1900.44	-8.44	351.63	-16.58	67.58	27.19
Group Means Per Condition				1980.53	-2.62	426.04	0.89	55.28	28.22
N1M	Male	Bite-Bl&Mskng	hit	1886.38	-4.35	482.50	8.46	48.77	16.29
N2F	Female	Bite-Bl&Mskng	hit	N/A	N/A	N/A	N/A	N/A	N/A
N3M	Male	Bite-Bl&Mskng	hit	1872.77	-3.94	410.88	12.88	50.12	37.38
N4F	Female	Bite-Bl&Mskng	hit	2134.81	-6.53	651.06	36.67	58.37	37.23
N5M	Male	Bite-Bl&Mskng	hit	1923.38	0.66	454.25	11.43	53.30	26.69
N6M	Male	Bite-Bl&Mskng	hit	1728.93	-16.71	485.67	15.22	53.19	36.52
Group Means Per Condition				1909.25	-6.17	496.87	16.93	52.75	30.82
N1M	Male	Masking	hit	1876.44	-4.86	459.88	3.37	42.02	10.62
N2F	Female	Masking	hit	N/A	N/A	N/A	N/A	N/A	N/A
N3M	Male	Masking	hit	1900.63	-2.51	416.88	14.53	64.58	43.44
N4F	Female	Masking	hit	2160.75	-5.39	565.94	18.80	53.01	42.69
N5M	Male	Masking	hit	1929.81	1.00	477.69	17.18	49.65	16.92
N6M	Male	Masking	hit	1982.25	-4.50	430.94	2.24	47.56	20.64
Group Means Per Condition				1969.98	-3.25	470.26	11.22	51.36	26.86

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Table 7.1c.--Group Means, % Change, and Standard Deviations of F2 and F1 of Hat for Adults with Normal Hearing

Sub-ject	Sex	Condition	Vowel	Mean F2	%Ch in F2	Mean F1	%Ch in F1	F2 SD	F1 SD
N1M	Male	Normal	hat	1612.14	***	589.14	***	23.17	19.13
N2F	Female	Normal	hat	1990.88	***	740.19	***	68.63	30.56
N3M	Male	Normal	hat	1711.13	***	844.69	***	36.65	33.40
N4F	Female	Normal	hat	1883.77	***	890.71	***	43.26	68.26
N5M	Male	Normal	hat	1540.00	***	782.69	***	37.38	41.58
N6M	Male	Normal	hat	1631.94	***	720.69	***	38.70	32.24
Group Means Per Condition				1728.31	***	761.35	***	41.30	37.53
N1M	Male	Bite-Block	hat	1642.13	1.86	732.00	24.25	33.93	37.76
N2F	Female	Bite-Block	hat	1921.39	-3.49	878.39	18.67	82.90	59.61
N3M	Male	Bite-Block	hat	1706.44	-0.27	777.75	-7.92	38.04	47.98
N4F	Female	Bite-Block	hat	1910.69	1.43	769.50	-13.61	97.40	110.07
N5M	Male	Bite-Block	hat	1473.69	-4.31	779.75	-0.38	45.15	32.53
N6M	Male	Bite-Block	hat	1540.13	-5.63	667.63	-7.36	71.59	43.01
Group Means Per Condition				1699.08	-1.73	767.50	2.27	61.50	55.16
N1M	Male	Bite-Bl&Mskng	hat	1597.93	-0.88	709.00	20.34	28.90	72.30
N2F	Female	Bite-Bl&Mskng	hat	1890.00	-5.07	906.31	22.44	63.29	56.70
N3M	Male	Bite-Bl&Mskng	hat	1606.18	-6.13	768.35	-9.04	41.28	51.94
N4F	Female	Bite-Bl&Mskng	hat	1910.40	1.41	1009.93	13.39	44.53	109.26
N5M	Male	Bite-Bl&Mskng	hat	1455.31	-5.50	808.56	3.31	27.32	22.14
N6M	Male	Bite-Bl&Mskng	hat	1442.38	-11.62	706.44	-1.98	41.37	27.29
Group Means Per Condition				1650.37	-4.63	818.10	8.08	41.12	56.60
N1M	Male	Masking	hat	1542.69	-4.31	641.13	8.82	23.67	50.03
N2F	Female	Masking	hat	1900.60	-4.53	715.13	-3.39	62.38	36.71
N3M	Male	Masking	hat	1688.38	-1.33	842.81	-0.22	23.24	45.38
N4F	Female	Masking	hat	1949.13	3.47	980.81	10.12	80.13	89.79
N5M	Male	Masking	hat	1513.06	-1.75	856.44	9.42	19.38	52.22
N6M	Male	Masking	hat	1574.31	-3.53	728.75	1.12	43.47	51.30
Group Means Per Condition				1694.69	-2.00	794.18	4.31	42.05	54.24

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Direction of Change

The second formant measurements were examined for overall differences among conditions. The bar graphs on the left side of Figure 7.1 revealed that, averaged across the group, there were modest changes in F2 in test conditions compared to the normal condition (the mean of which was represented by zero). As predicted by computer simulation, both test conditions employing a bite block (B and B+M) resulted in a lowering of F2 from the normal condition. The masking condition (M) also resulted in a lowered mean F2.

First formant measurements were next examined for overall differences among conditions. The bar graphs on the right side of Figure 7.1 revealed that, averaged across the group, there were larger changes in F1 than in F2 in test conditions compared to the normal condition (the mean of which was again represented by zero). As predicted by computer simulation, both test conditions employing a bite block (B and B+M) resulted in a raising of F1 from the normal condition. Therefore, the bar graphs depicting changes in F1 on the right side of the figure are in the reverse direction of those depicting changes in F2 on the left side of the figure. As in the case of F2, the masking condition (M) produced changes in F1 in the same direction as in bite-block conditions.

Magnitude of Change

Figure 7.1 revealed that the test conditions produced modest changes in F2 in a pattern that was very similar for the three vowels. The magnitude of the lowering was virtually the same for bite-block and masking conditions (4% or less), while the combination of masking and bite block was roughly additive (7% or less). To determine whether any of the observed differences were statistically significant, a repeated measures one-way analysis of variance by condition was performed separately for each vowel because Subjects N2F and N5M had missing data for /I/ and /i/, respectively. (See Tables 7.1a and 7.1b.) Individual mean F2 measurements in Hertz served as the raw data. The results of the repeated measures ANOVA for F2 are reported in Table 7.2a for each vowel.

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The main effect of condition was greatest for /i/ F2 (p=0.0004), but was also significant for /ae/ F2 (p=0.0368). In both cases, post hoc Least Significant Difference (LSD) tests of paired comparisons between the F2 means in each condition, shown in Table 7.3a and 7.3b, revealed that the bite-block-plus-masking condition lowered F2 most in both vowels. Furthermore, the post hoc tests of the main effect of condition on /i/ F2 supported the observations made earlier, that both the bite-block and masking conditions significantly lowered F2 from the normal condition (N v. BB, p=0.01724 and N v. M, p=0.01848) and were very similar in their effect (BB v. M, p=.97065). The bite-block-plus-masking condition lowered F2 substantially more than either bite block or masking alone (BB v. B+M, p=0.00419 and B+M v. M, p=0.00391). While the lowering effect for hit F2 looked similar to that for the other vowels in Figure 7.1, the upper left graph of Figure 7.2 shows that, in the normal condition, hit F2 variability was greater than for the other vowels. It is because of the increased variability of /I/ that the effect is less significant, though of similar magnitude.

The graphs on the right side of Figure 7.1 showed that test conditions produced larger changes in F1 than in F2, some as large as 17%. For /I/ and /ae/, the bite block alone seemed to have little effect, but masking alone had an effect, and the bite block had an additional effect when masking was present. However, the data for /i/ looked quite different. The bite block alone had an effect, but no extra effect when masking was present. The statistical results indicated that only the largest changes in hit resulted in a significant main effect of condition (p=0.0136). (See Table 7.2b.) Post hoc LSD tests of differences between the /I/ F1 means in each condition, shown in Table 7.3c, revealed that the bite-block-plus-masking condition substantially raised /I/ F1 from the normal condition (N v. B+M, p=0.00526) and from the bite-block condition, which had almost no effect (BB v. B+M, p=0.00687).

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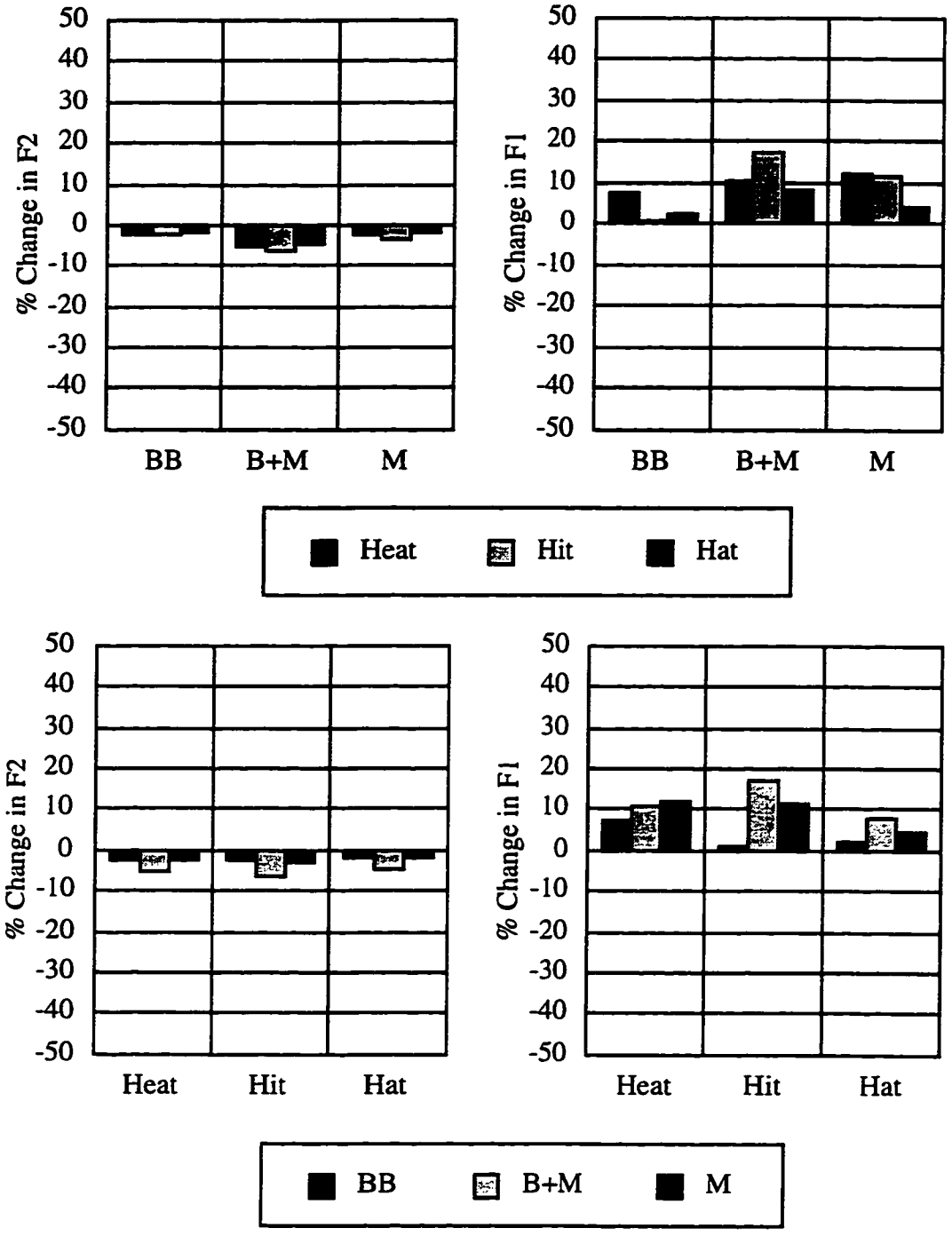


Fig. 7.1. Mean % Change from Normal Condition in F2 and F1 in Bite-Block (BB), Bite-Block-Plus-Masking (B+M), and Masking (M) Conditions for Adults with Normal Hearing

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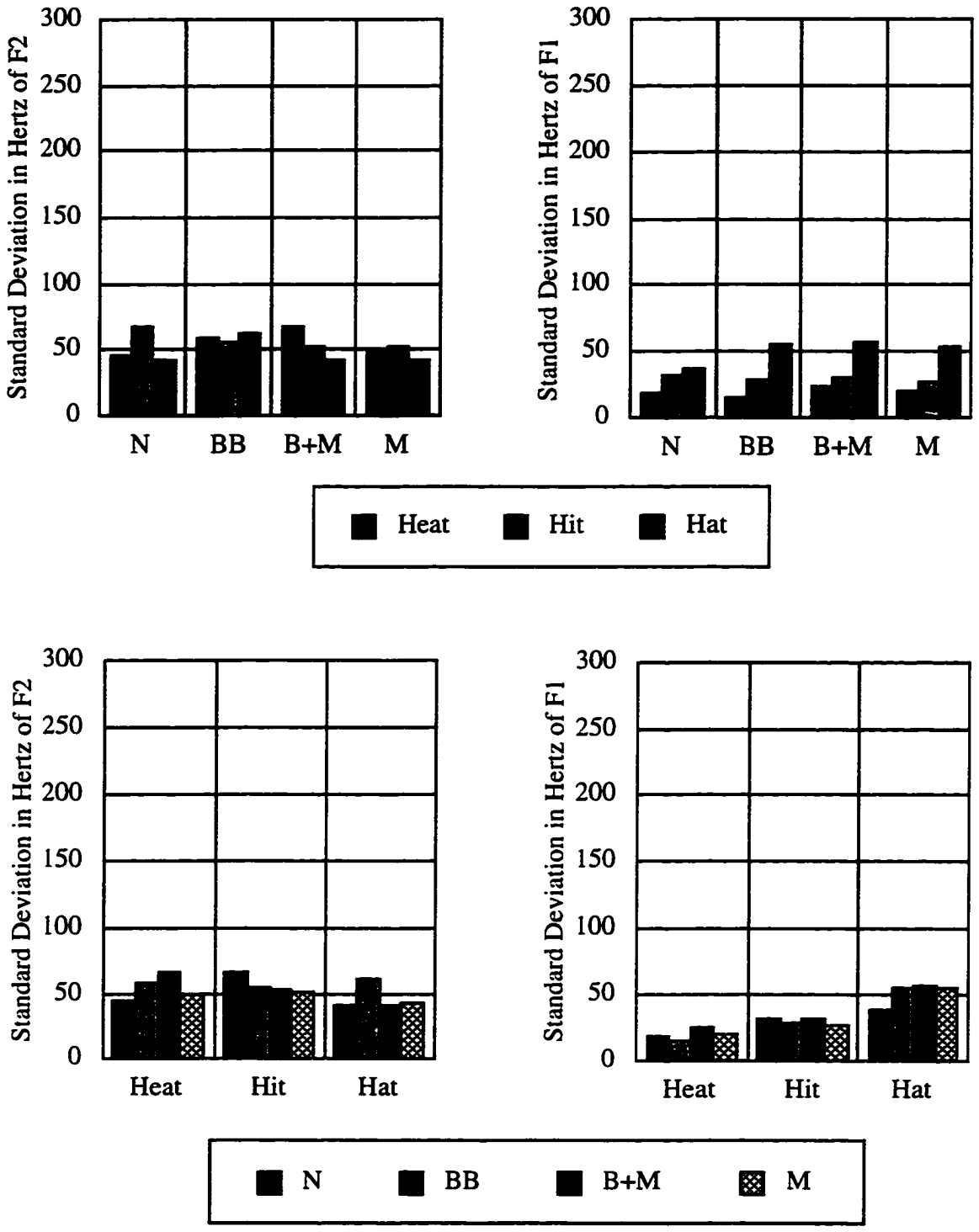


Fig. 7.2. Mean Standard Deviation in Hertz of F2 and F1 for Each Vowel in Normal (N), Bite-Block (BB), Bite-Block-Plus-Masking (B+M), and Masking (M) Conditions for Adults with Normal Hearing

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Table 7.2a.--Repeated Measures One-Way Analysis of Variance: Mean F2 for Group of Adults with Normal Hearing

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Heat					
Condition	49541.68	3	16513.89	13.28	.0004★★
Error	14923.07	12	1243.59		
Hit					
Condition	41999.05	3	13999.68	2.76	.0878
Error	60773.29	12	5064.44		
Hat					
Condition	18625.21	3	6208.40	3.66	.0368★
Error	25426.60	15	1695.11		

Table 7.2b.--Repeated Measures One-Way Analysis of Variance: Mean F1 for Group of Adults with Normal Hearing

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Heat					
Condition	3268.38	3	1089.46	2.56	.1042
Error	5114.60	12	426.22		
Hit					
Condition	19262.72	3	6420.91	5.43	.0136★
Error	14194.80	12	1182.90		
Hat					
Condition	12268.79	3	4089.60	.82	.5005
Error	74388.37	15	4959.23		

Table 7.2c.--Repeated Measures One-Way Analysis of Variance: Mean Standard Deviation of F2 for Group of Adults with Normal Hearing

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Heat					
Condition	1402.15	3	467.38	.56	.6523
Error	10039.61	12	836.63		
Hit					
Condition	709.39	3	236.46	.94	.4508
Error	3011.76	12	250.98		
Hat					
Condition	1805.71	3	601.90	4.56	.0184★
Error	1980.85	15	132.06		

★★ = $p<.01$, ★ = $p<.05$

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Table 7.2d.--Repeated Measures One-Way Analysis of Variance: Mean Standard Deviation of F1 for Group of Adults with Normal Hearing

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Heat					
Condition	201.54	3	67.18	1.14	.3714
Error	705.53	12	58.79		
Hit					
Condition	82.91	3	27.64	.70	.5682
Error	471.67	12	39.31		
Hat					
Condition	1443.84	3	481.28	2.51	.0983
Error	2877.28	15	191.82		

★★ = p<.01, ★ = p<.05

The mean standard deviations in Hertz of F2 and F1 were next examined (Figure 7.2) to determine if there were overall differences among conditions in terms of variability of production. (See Tables 7.2c and 7.2d.) No significant main effect of condition was shown for F1 standard deviation, but /ae/ F2 standard deviation showed a main effect of condition. (See Table 7.2c.) Post hoc LSD tests of this main effect indicated that the bite block alone resulted in a substantial increase in F2 variability compared to the normal and to the other two test conditions. (See Table 7.3d.)

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Table 7.3a.--Summary of Results of Post Hoc Tests of the Main Effect of Condition on Heat F2 for Adults with Normal Hearing

Mean /i/ F2 in Four Conditions:			
N = 2556.75	BB = 2495.17	B+M = 2416.55	M = 2496.00
	N v. BB	p = 0.01724★	
	N v. B+M	p = 0.00004★★	
	N v. M	p = 0.01848★	
	BB v. B+M	p = 0.00419★★	
	BB v. M	p = 0.97065	
	B+M v. M	p = 0.00391★★	

Table 7.3b.--Summary of Results of Post Hoc Tests of the Main Effect of Condition on Hat F2 for Adults with Normal Hearing

Mean /ae/ F2 in Four Conditions:			
N = 1728.31	BB = 1699.08	B+M = 1650.37	M = 1694.70
	N v. BB	p = 0.23773	
	N v. B+M	p = 0.00507★★	
	N v. M	p = 0.17774	
	BB v. B+M	p = 0.05835	
	BB v. M	p = 0.85617	
	B+M v. M	p = 0.08189	

Table 7.3c.--Summary of Results of Post Hoc Tests of the Main Effect of Condition on Hit F1 for Adults with Normal Hearing

Mean /I/ F1 in Four Conditions:			
N = 422.89	BB = 426.04	B+M = 496.87	M = 470.27
	N v. BB	p = 0.88719	
	N v. B+M	p = 0.00526★★	
	N v. M	p = 0.05006	
	BB v. B+M	p = 0.00687★★	
	BB v. M	p = 0.06476	
	B+M v. M	p = 0.24475	

Table 7.3d.--Summary of Results of Post Hoc Tests of the Main Effect of Condition on Hat F2SD for Adults with Normal Hearing

Mean /ae/ F2SD in Four Conditions:			
N = 41.30	BB = 61.50	B+M = 41.11	M = 42.04
	N v. BB	p = 0.00818★★	
	N v. B+M	p = 0.97832	
	N v. M	p = 0.91189	
	BB v. B+M	p = 0.00774★★	
	BB v. M	p = 0.01029★	
	B+M v. M	p = 0.89039	

★★ = p<.01, ★ = p<.05

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Summary

In this chapter, and all subsequent results chapters, summary tables like Tables 7.4 - 7.9 below will be used to consolidate, compare, and contrast bite-block, masking, and bite-block-plus masking effects for all dependent variables across all subject groups. Columns for results from subsequent chapters appear in gray now. The information from post hoc tests is provided, of course, only where a significant main effect of condition was obtained for a dependent variable.

The data from the group of adults with normal hearing revealed that:

A. the bite block lowered F2 and raised F1, as predicted by computer simulation. Heat F2 was lowered significantly. (See Table 7.4.)

B. the masking condition resulted in changes in F2 and F1 in the same directions as the bite block. Heat F2 was lowered significantly. (See Table 7.5.)

C. the bite-block-plus-masking condition also changed F2 and F1 in the same directions as the bite block alone and masking alone. Heat and hat F2 were lowered significantly. For heat, the bite-block-plus-masking lowering effect was significantly greater than that of either the bite block alone or masking alone. Hit F1 was significantly raised from the normal condition and from the bite-block condition, which had almost no effect. (See Table 7.6.)

D. the bite block significantly increased /ae/ F2 variability, but the masking and bite-block-plus-masking conditions did not. (See Tables 7.7 - 7.9.)

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Table 7.4.--Summary of Bite-Block Effects on F2 and F1 for Groups of Subjects

	Adults with Normal Hearing	Children with Normal Hearing	Adults with Profound Hearing Loss	Adults with Severe Hearing Loss
F2 Direction of Change: heat hit hat	 lowered lowered lowered			
% Change	<3%			
Post Hoc Tests of Main Effect of Condition for Heat: N v. BB Hit: N v. BB Hat: N v. BB	↓ ★			
F1 Direction of Change: heat hit hat	 raised raised raised			
% Change	<8%			
Post Hoc Tests of Main Effect of Condition for Heat: N v. BB Hit: N v. BB Hat: N v. BB				

★★=p<.01, ★=p<.05, ↑ = raised formant, ↓ = lowered formant

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Table 7.5.--Summary of Masking Effects on F2 and F1 for Groups of Subjects

	Adults with Normal Hearing	Children with Normal Hearing	Adults with Profound Hearing Loss	Adults with Severe Hearing Loss
F2 Direction of Change:				
heat	lowered			
hit	lowered			
hat	lowered			
% Change	<4%			
Post Hoc Tests of Main Effect of Condition for Heat:				
N v. M	↓ ★			
BB v. M				
Hit:				
N v. M				
BB v. M				
Hat:				
N v. M				
BB v. M				
F1 Direction of Change:				
heat	raised			
hit	raised			
hat	raised			
% Change	<12%			
Post Hoc Tests of Main Effect of Condition for Heat:				
N v. M				
BB v. M				
Hit:				
N v. M				
BB v. M				
Hat:				
N v. M				
BB v. M				

★★=p<.01, ★=p<.05, ↑ = raised formant, ↓ = lowered formant

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Table 7.6.--Summary of Bite-Block-Plus-Masking Effects on F2 and F1 for Groups of Subjects

	Adults with Normal Hearing	Children with Normal Hearing	Adults with Profound Hearing Loss	Adults with Severe Hearing Loss
F2 Direction of Change:				
heat	lowered			
hit	lowered			
hat	lowered			
% Change	<7%			
Post Hoc Tests of Main Effect of Condition for Heat:				
N v. BM	↓ ★★			
BB v. B+M	★★			
M v. B+M	★★			
Hit:				
N v. BM				
BB v. B+M				
M v. B+M				
Hat:				
N v. BM	↓ ★★			
BB v. B+M				
M v. B+M				
F1 Direction of Change:				
heat	raised			
hit	raised			
hat	raised			
% Change	<17%			
Post Hoc Tests of Main Effect of Condition for Heat:				
N v. BM				
BB v. B+M				
M v. B+M				
Hit:				
N v. BM	↑ ★★			
BB v. B+M	★★			
M v. B+M				
Hat:				
N v. BM				
BB v. B+M				
M v. B+M				

★★=p<.01, ★=p<.05, ↑ = raised formant, ↓ = lowered formant

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Table 7.7.--Summary of Bite-Block Effects on F2SD and F1SD for Groups of Subjects

	Adults with Normal Hearing	Children with Normal Hearing	Adults with Profound Hearing Loss	Adults with Severe Hearing Loss
Post Hoc Tests of Main Effect of Condition for Heat F2SD: N v. BB				
Hit F2SD: N v. BB				
Hat F2SD: N v. BB	↑ ★★			
Post Hoc Tests of Main Effect of Condition for Heat F1SD: N v. BB				
Hit F1SD: N v. BB				
Hat F1SD: N v. BB				

★★=p<.01, ★=p<.05, ↑ = increased variability, ↓ = decreased variability

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Table 7.8.--Summary of Masking Effects on F2SD and F1SD for Groups of Subjects

	Adults with Normal Hearing	Children with Normal Hearing	Adults with Profound Hearing Loss	Adults with Severe Hearing Loss
Post Hoc Tests of Main Effect of Condition for Heat F2SD:				
N v. M				
BB v. M				
Hit F2SD:				
N v. M				
BB v. M				
Hat F2SD:				
N v. M				
BB v. M	★			
Post Hoc Tests of Main Effect of Condition for Heat F1SD:				
N v. M				
BB v. M				
Hit F1SD:				
N v. M				
BB v. M				
Hat F1SD:				
N v. M				
BB v. M				

★★=p<.01, ★=p<.05, ↑ = increased variability, ↓ = decreased variability

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Table 7.9.--Summary of Bite-Block-Plus-Masking Effects on F2SD and F1SD for Groups of Subjects

	Adults with Normal Hearing	Children with Normal Hearing	Adults with Profound Hearing Loss	Adults with Severe Hearing Loss
Post Hoc Tests of Main Effect of Condition for Heat F2SD:				
N v. B+M				
BB v. B+M				
M v. B+M				
Hit F2SD:				
N v. B+M				
BB v. B+M				
M v. B+M				
Hat F2SD:				
N v. B+M				
BB v. B+M	★★			
M v. B+M				
Post Hoc Tests of Main Effect of Condition for Heat F1SD:				
N v. B+M				
BB v. B+M				
M v. B+M				
Hit F1SD:				
N v. B+M				
BB v. B+M				
M v. B+M				
Hat F1SD:				
N v. B+M				
BB v. B+M				
M v. B+M				

★★=p<.01, ★=p<.05, ↑ = increased variability, ↓ = decreased variability

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Individual Data

In general, averages across a group of talkers do not adequately reflect the attributes of individual speech production systems. To discover the distinctive patterns of compensatory adjustments made by individuals in response to test conditions, the data from each talker were analyzed separately. (See Tables 7.10 - 7.15 and Figures 7.3 - 7.8.)

Direction of Change

F2

For most talkers F2 was lowered for vowels spoken in test conditions employing a bite block (BB and B+M). This was consistent with predictions from computer simulation and with the data averaged across the group of adults with normal hearing. In addition, F2 was lowered for vowels spoken in the masking noise condition. The direction of that change was also consistent with group data. A lowered F2 for test conditions was shown without variation for Subjects N2F (Table 7.11 and Figure 7.4) and N6M (Table 7.15 and Figure 7.8).

The exceptions were few. Subject N1M (Table 7.10 and Figure 7.3) exhibited a pattern of raising F2 in the bite-block condition for all three vowels. It appeared that he made an "over adjustment" or an "over compensation" for the presence of the bite block when auditory feedback was normal. For Subject N4F (Table 7.13 and Figure 7.6) F2 was raised for all test conditions for hat. It will be remembered from "Chapter Four: Computer Simulation of Bite-Block Effects on Formant Frequency" that computer simulation predicted that the formant values for the open vowel /ae/ may be either raised or lowered in a bite-block condition, depending on whether the bite block creates a less-than-normal or greater-than-normal interincisor distance for a specific talker. Although Subject N4F is a female speaker, and thus might have been expected to have a smaller vocal tract than a male speaker, it may well have been the case that the bite-block conditions (BB and B+M) created a less-than-normal interincisor distance for her production of hat and resulted

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in a raised F2, although that does not account for a similar raising of F2 for the masking condition.

F1

For most talkers F1 was raised for heat and hit spoken in test conditions employing a bite block (BB and B+M). This was consistent with predictions from computer simulation and with the data averaged across the group of adults with normal hearing. However, F1 was lowered for /ae/ as many times as it was raised. In the bite-block and bite-block-plus-masking conditions, hat F1 was raised in subjects N1M and N2F and lowered in N3M and N6M. (See Tables 7.10, 7.11, 7.12 and 7.15; Figures 7.3, 7.4, 7.5 and 7.8.) In subjects N4F and N5M, /ae/ F1 was lowered in the bite-block condition, but raised in the bite-block-plus-masking condition. Collapsed across the two conditions (B and B+M) the overall effect was one of lowering. Again, it will be remembered that computer simulation predicted that the formant values for /ae/ might be either raised or lowered in a bite-block condition, depending on whether the bite block created a less-than-normal or greater-than-normal interincisor distance for a specific talker. N3M, N5M and N6M, who had exhibited a lowered F2 in the bite-block and bite-block-plus-masking conditions for hat, also exhibited lowered /ae/ F1 values. (See Tables 7.12, 7.14 and 7.15; Figures 7.5, 7.7 and 7.8.) These changes in formant values from the normal condition for hat suggest that the tongue might have been adjusted to a higher position farther back in the mouth in bite-block conditions.

The effect of masking on heat and hit F1 was in the same direction as the effect of bite block, a raised formant value. The direction of that change was also consistent with group data. The masking effect on hat F1 was also to raise it in a majority of cases, however, this direction of change was opposite to that in bite-block conditions for four of the six subjects: N2F, N4F, N5M and N6M (See Tables 7.11, 7.13, 7.14 and 7.15; Figures 7.4, 7.6, 7.7 and 7.8.)

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Table 7.10.--Subject N1M: Means, Standard Deviations and Percent Change in Formants from Normal Condition to Test Conditions

Vowel	Condition	N	Mean F2	% Ch F2	Mean F1	% Ch F1	F2 St Dev	F1 St Dev
Heat	Normal	12	2345.50	***	243.33	***	24.12	8.53
	Bite Block	14	2350.86	0.23	262.71	7.96	26.08	8.81
	Bite Block and Masking	13	2261.39	-3.59	269.39	10.71	59.80	6.50
	Masking	11	2299.18	-1.97	256.36	5.36	35.54	8.82
Hit	Normal	16	1972.25	***	444.88	***	51.38	14.35
	Bite Block	16	2026.00	2.73	461.50	3.74	27.77	25.87
	Bite Block and Masking	16	1886.38	-4.35	482.50	8.46	48.77	16.29
	Masking	16	1876.44	-4.86	459.88	3.37	42.02	10.62
Hat	Normal	14	1612.14	***	589.14	***	23.17	19.13
	Bite Block	15	1642.13	1.86	732.00	24.25	33.93	37.76
	Bite Block and Masking	15	1597.93	-0.88	709.00	20.34	28.90	72.30
	Masking	16	1542.69	-4.31	641.13	8.82	23.67	50.03

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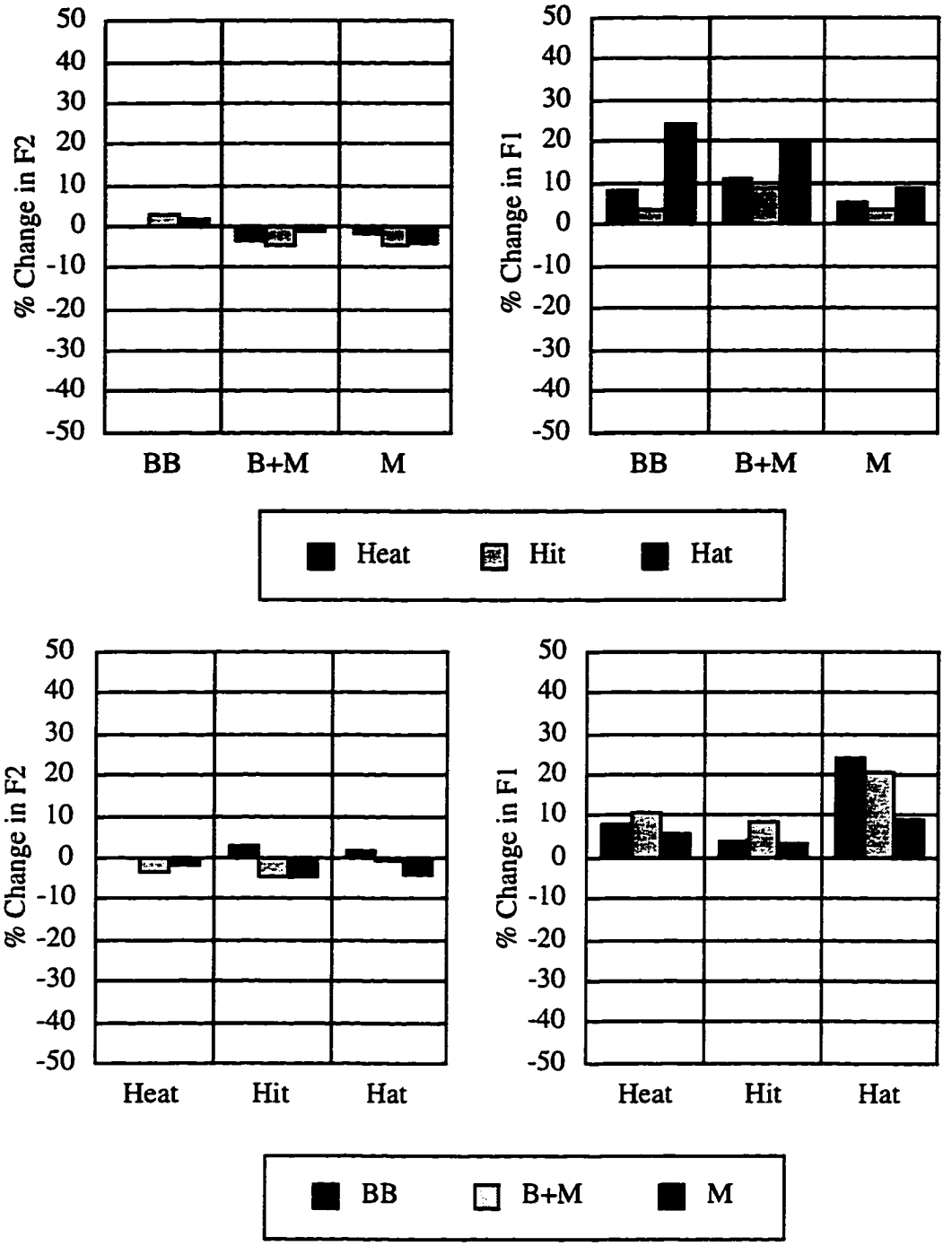


Fig. 7.3. % Change from Normal Condition in F2 and F1 in Bite-Block (BB), Bite-Block-Plus-Masking (B+M), and Masking (M) Conditions for Subject N1M

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Table 7.11.--Subject N2F: Means, Standard Deviations and Percent Change in Formants from Normal Condition to Test Conditions

Vowel	Condition	N	Mean F2	% Ch F2	Mean F1	% Ch F1	F2 St Dev	F1 St Dev
Heat	Normal	15	2820.07	***	328.20	***	46.93	35.93
	Bite Block	13	2778.85	-1.46	305.15	-7.02	59.09	17.55
	Bite Block and Masking	14	2635.07	-6.56	332.57	1.33	111.79	28.25
	Masking	16	2808.06	-0.43	370.75	12.96	51.68	24.85
Hit	Normal	3	N/A[1]	N/A	N/A	N/A	N/A	N/A
	Bite Block	15	N/A	N/A	N/A	N/A	N/A	N/A
	Bite Block and Masking	13	N/A	N/A	N/A	N/A	N/A	N/A
	Masking	11	N/A	N/A	N/A	N/A	N/A	N/A
Hat	Normal	16	1990.88	***	740.19	***	68.63	30.56
	Bite Block	13	1921.39	-3.49	878.39	18.67	82.90	59.61
	Bite Block and Masking	16	1890.00	-5.07	906.31	22.44	63.29	56.70
	Masking	15	1900.60	-4.53	715.13	-3.39	62.38	36.71

[1]All but three tokens in the Normal condition for hit were rejected, because the F1 measures were resolved over very narrow bandwidths. Criterion for inclusion of a condition was a minimum of 8 tokens in which both F1 and F2 measures were obtained. The loss of the Normal condition, against which all the test conditions were compared, then required that all test condition measures be rejected.

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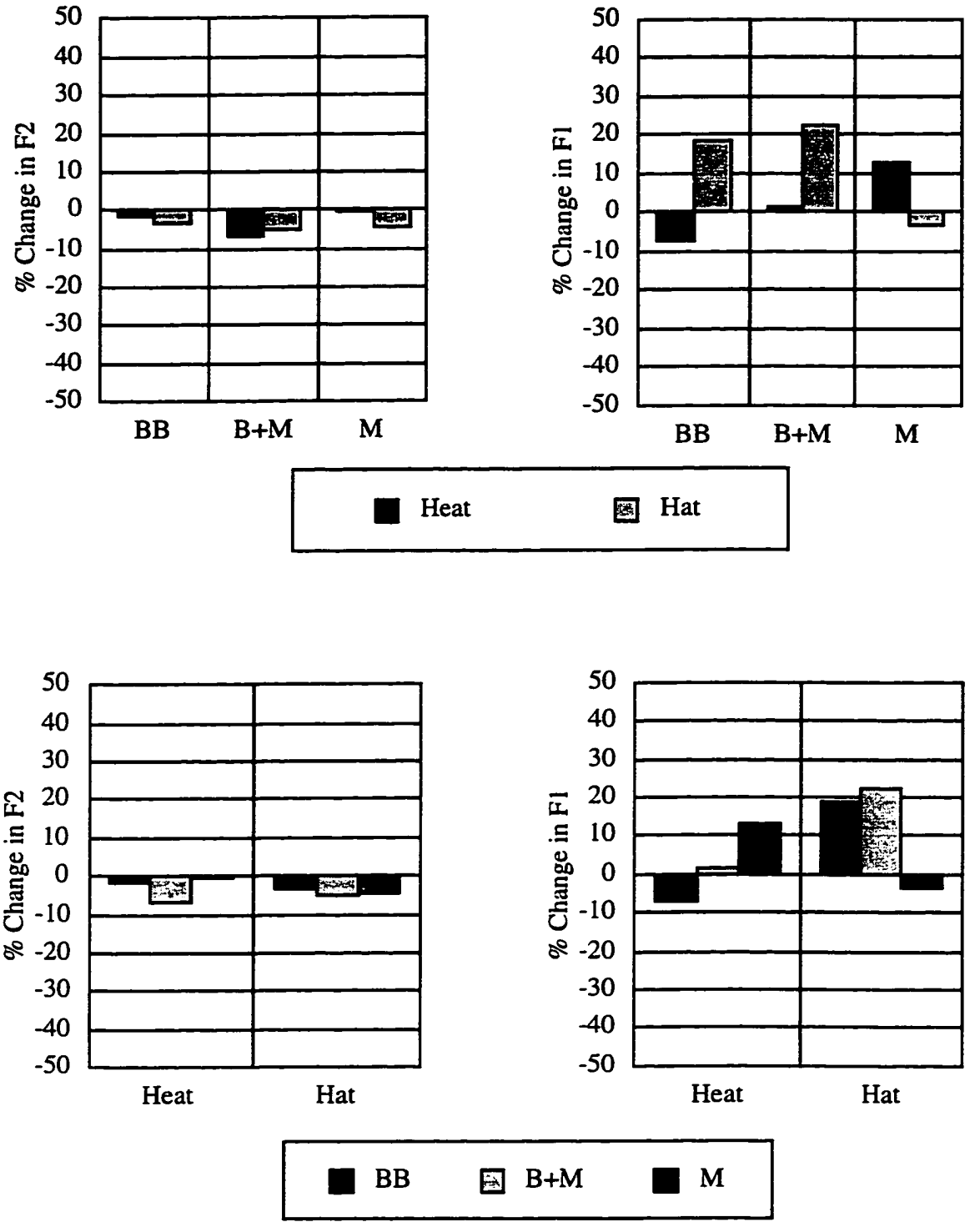


Fig. 7.4. % Change from Normal Condition in F2 and F1 in Bite-Block (BB), Bite-Block-Plus-Masking (B+M), and Masking (M) Conditions for Subject N2F

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Table 7.12.--Subject N3M: Means, Standard Deviations and Percent Change in Formants from Normal Condition to Test Conditions

Vowel	Condition	N	Mean F2	% Ch F2	Mean F1	% Ch F1	F2 St Dev	F1 St Dev
Heat	Normal	16	2368.38	***	242.88	***	73.76	11.66
	Bite Block	16	2297.06	-3.01	259.38	6.79	29.36	17.97
	Bite Block and Masking	16	2273.56	-4.00	293.13	20.69	48.94	23.91
	Masking	15	2282.13	-3.64	273.93	12.79	47.06	21.03
Hit	Normal	16	1949.56	***	364.00	***	42.15	41.48
	Bite Block	16	1958.06	0.44	395.50	8.65	39.92	36.41
	Bite Block and Masking	17	1872.77	-3.94	410.88	12.88	50.12	37.38
	Masking	16	1900.63	-2.51	416.88	14.53	64.58	43.44
Hat	Normal	16	1711.13	***	844.69	***	36.65	33.40
	Bite Block	16	1706.44	-0.27	777.75	-7.92	38.04	47.98
	Bite Block and Masking	17	1606.18	-6.13	768.35	-9.04	41.28	51.94
	Masking	16	1688.38	-1.33	842.81	-0.22	23.24	45.38

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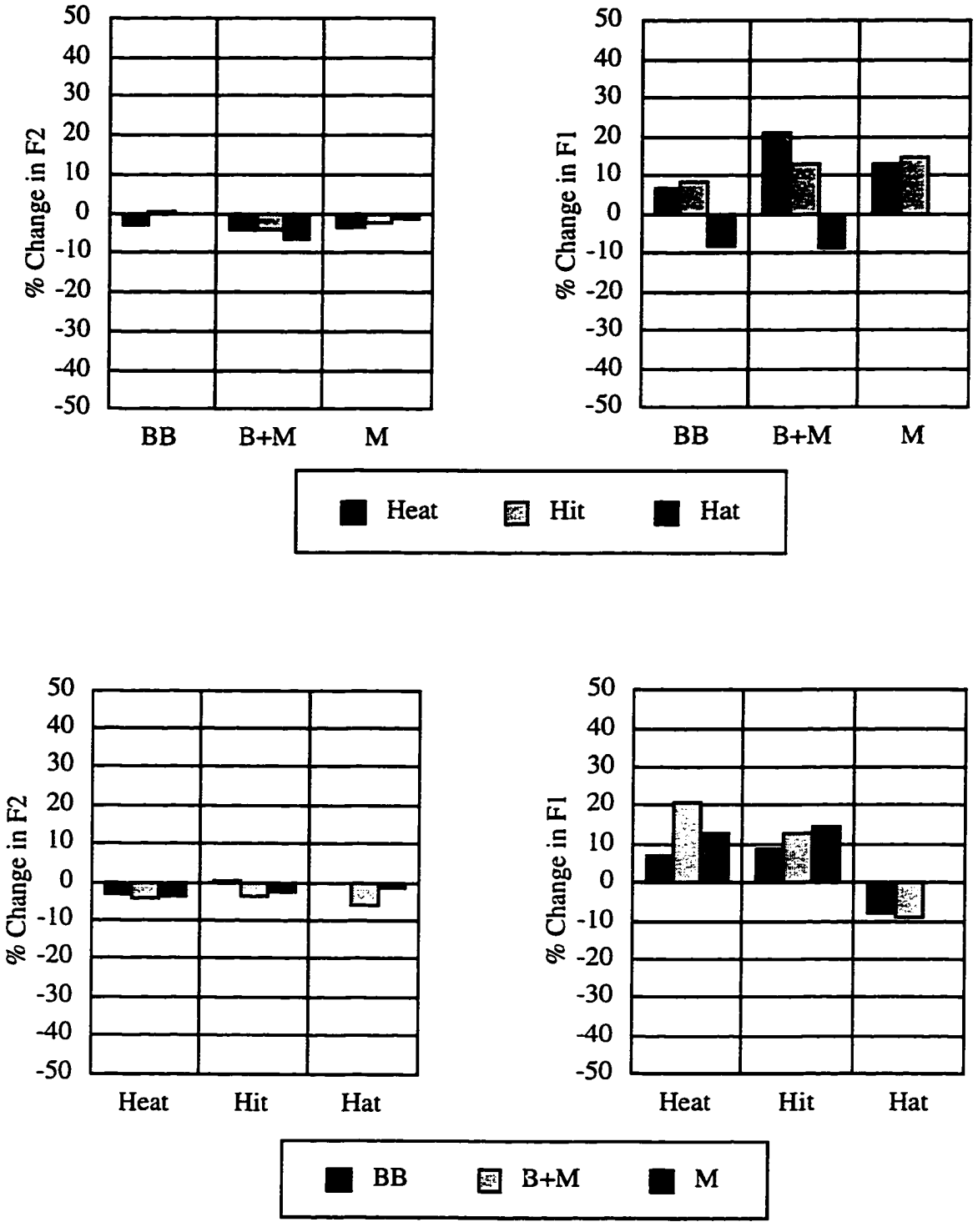


Fig. 7.5. % Change from Normal Condition in F2 and F1 in Bite-Block (BB), Bite-Block-Plus-Masking (B+M), and Masking (M) Conditions for Subject N3M

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Table 7.13.--Subject N4F: Means, Standard Deviations and Percent Change in Formants from Normal Condition to Test Conditions

Vowel	Condition	N	Mean F2	% Ch F2	Mean F1	% Ch F1	F2 St Dev	F1 St Dev
Heat	Normal	16	2906.50	***	316.81	***	35.08	21.89
	Bite Block	16	2848.81	-1.98	376.25	18.76	147.28	17.08
	Bite Block and Masking	15	2784.80	-4.19	318.20	0.44	66.38	49.91
	Masking	15	2863.27	-1.49	368.33	16.26	79.48	26.61
Hit	Normal	16	2283.88	***	476.38	***	90.97	52.11
	Bite Block	16	2117.31	-7.29	491.75	3.23	55.21	36.69
	Bite Block and Masking	16	2134.81	-6.53	651.06	36.67	58.37	37.23
	Masking	16	2160.75	-5.39	565.94	18.80	53.01	42.69
Hat	Normal	17	1883.77	***	890.71	***	43.26	68.26
	Bite Block	16	1910.69	1.43	769.50	-13.61	97.40	110.07
	Bite Block and Masking	15	1910.40	1.41	1009.93	13.39	44.53	109.26
	Masking	16	1949.13	3.47	980.81	10.12	80.13	89.79

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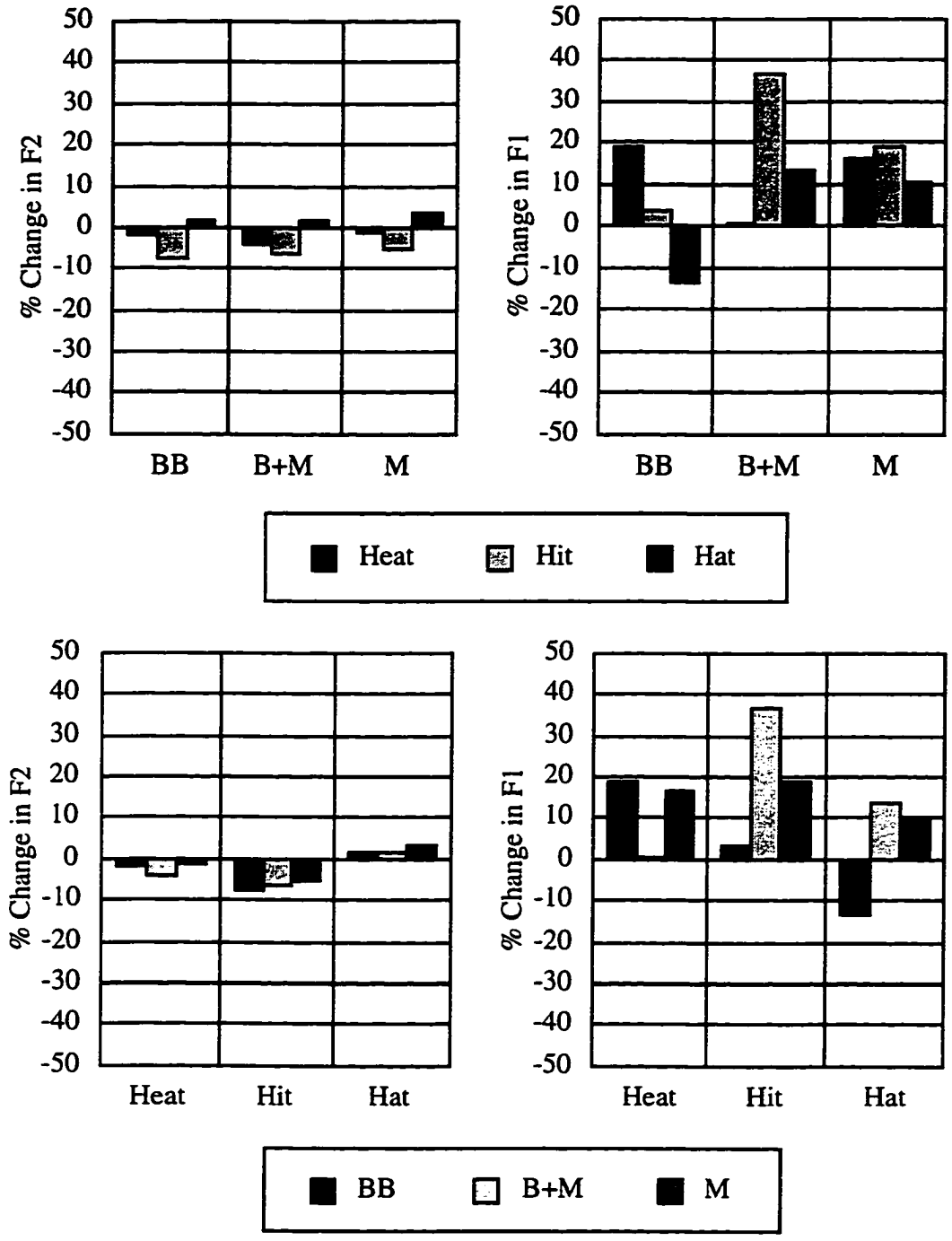


Fig. 7.6 % Change from Normal Condition in F2 and F1 in Bite-Block (BB), Bite-Block-Plus-Masking (B+M), and Masking (M) Conditions for Subject N4F

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Table 7.14.--Subject N5M: Means, Standard Deviations and Percent Change in Formants from Normal Condition to Test Conditions

Vowel	Condition	N	Mean F2	% Ch F2	Mean F1	% Ch F1	F2 St Dev	F1 St Dev
Heat	Normal	6	N/A[2]	N/A	N/A	N/A	N/A	N/A
	Bite Block	6	N/A	N/A	N/A	N/A	N/A	N/A
	Bite Block and Masking	16	N/A	N/A	N/A	N/A	N/A	N/A
	Masking	10	N/A	N/A	N/A	N/A	N/A	N/A
Hit	Normal	15	1910.73	***	407.67	***	55.35	17.47
	Bite Block	16	1900.81	-0.52	429.81	5.43	85.94	14.94
	Bite Block and Masking	16	1923.38	0.66	454.25	11.43	53.30	26.69
	Masking	16	1929.81	1.00	477.69	17.18	49.65	16.92
Hat	Normal	16	1540.00	***	782.69	***	37.38	41.58
	Bite Block	16	1473.69	-4.31	779.75	-0.38	45.15	32.53
	Bite Block and Masking	16	1455.31	-5.50	808.56	3.31	27.32	22.14
	Masking	16	1513.06	-1.75	856.44	9.42	19.38	52.22

[2]All but six tokens in the Normal condition for heat were rejected, because the F1 measures were resolved over very narrow bandwidths. Criterion for inclusion of a condition was a minimum of 8 tokens in which both F1 and F2 measures were obtained. The loss of the Normal condition, against which all the test conditions were compared, then required that all test condition measures be rejected.

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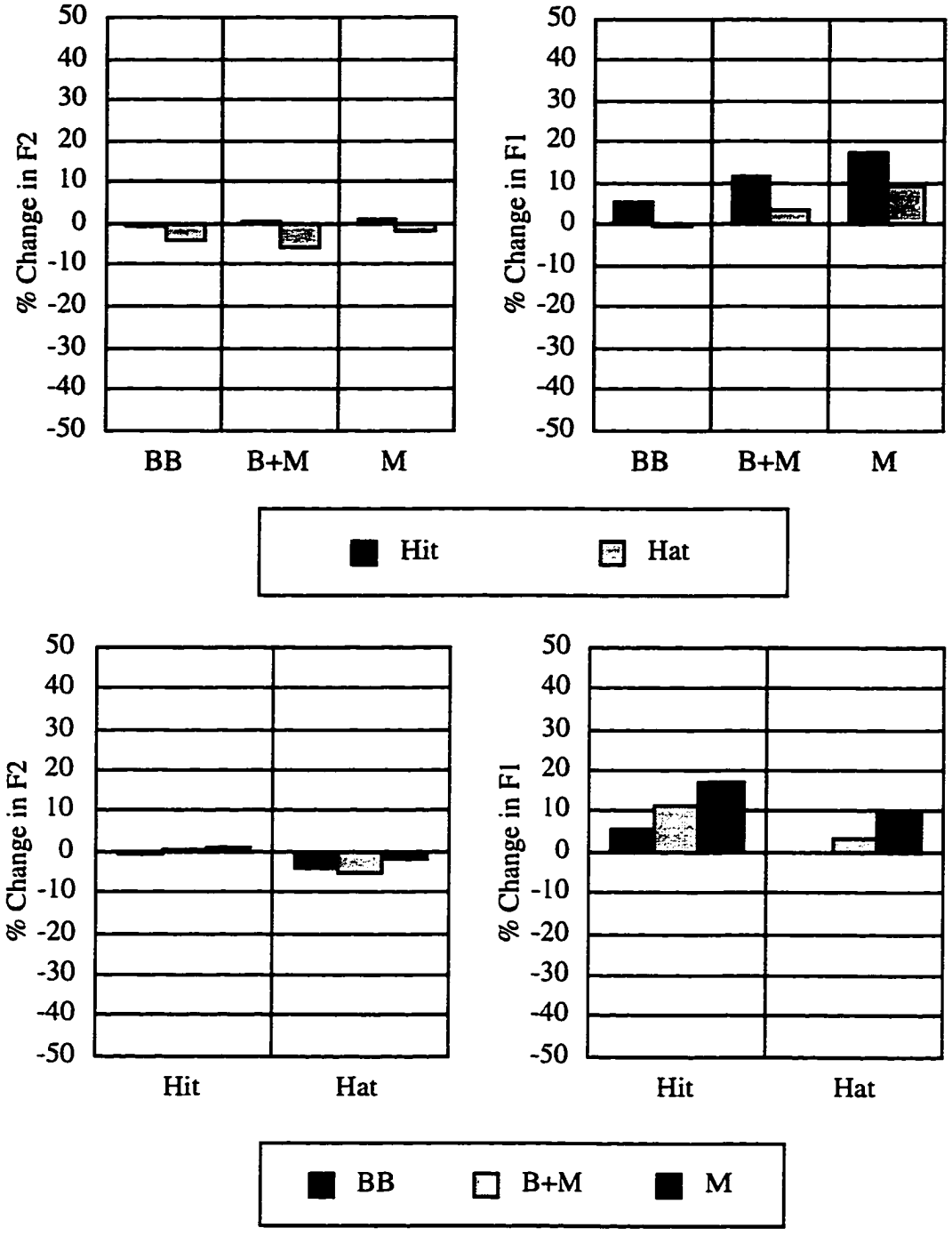


Fig. 7.7. % Change from Normal Condition in F2 and F1 in Bite-Block (BB), Bite-Block-Plus-Masking (B+M), and Masking (M) Conditions for Subject N5M

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Table 7.15.--Subject N6M: Means, Standard Deviations and Percent Change in Formants from Normal Condition to Test Conditions

Vowel	Condition	N	Mean F2	% Ch F2	Mean F1	% Ch F1	F2 St Dev	F1 St Dev
Heat	Normal	16	2343.31	***	271.00	***	45.71	13.98
	Bite Block	16	2200.25	-6.11	299.44	10.49	31.00	14.77
	Bite Block and Masking	15	2127.93	-9.19	322.93	19.16	46.06	11.87
	Masking	16	2227.38	-4.95	304.94	12.52	31.31	16.35
Hit	Normal	16	2075.69	***	421.50	***	92.64	34.58
	Bite Block	16	1900.44	-8.44	351.63	-16.58	67.58	27.19
	Bite Block and Masking	16	1728.93	-16.71	485.67	15.22	53.19	36.52
	Masking	16	1982.25	-4.50	430.94	2.24	47.56	20.64
Hat	Normal	16	1631.94	***	720.69	***	38.70	32.24
	Bite Block	16	1540.13	-5.63	667.63	-7.36	71.59	43.01
	Bite Block and Masking	16	1442.38	-11.62	706.44	-1.98	41.37	27.29
	Masking	16	1574.31	-3.53	728.75	1.12	43.47	51.30

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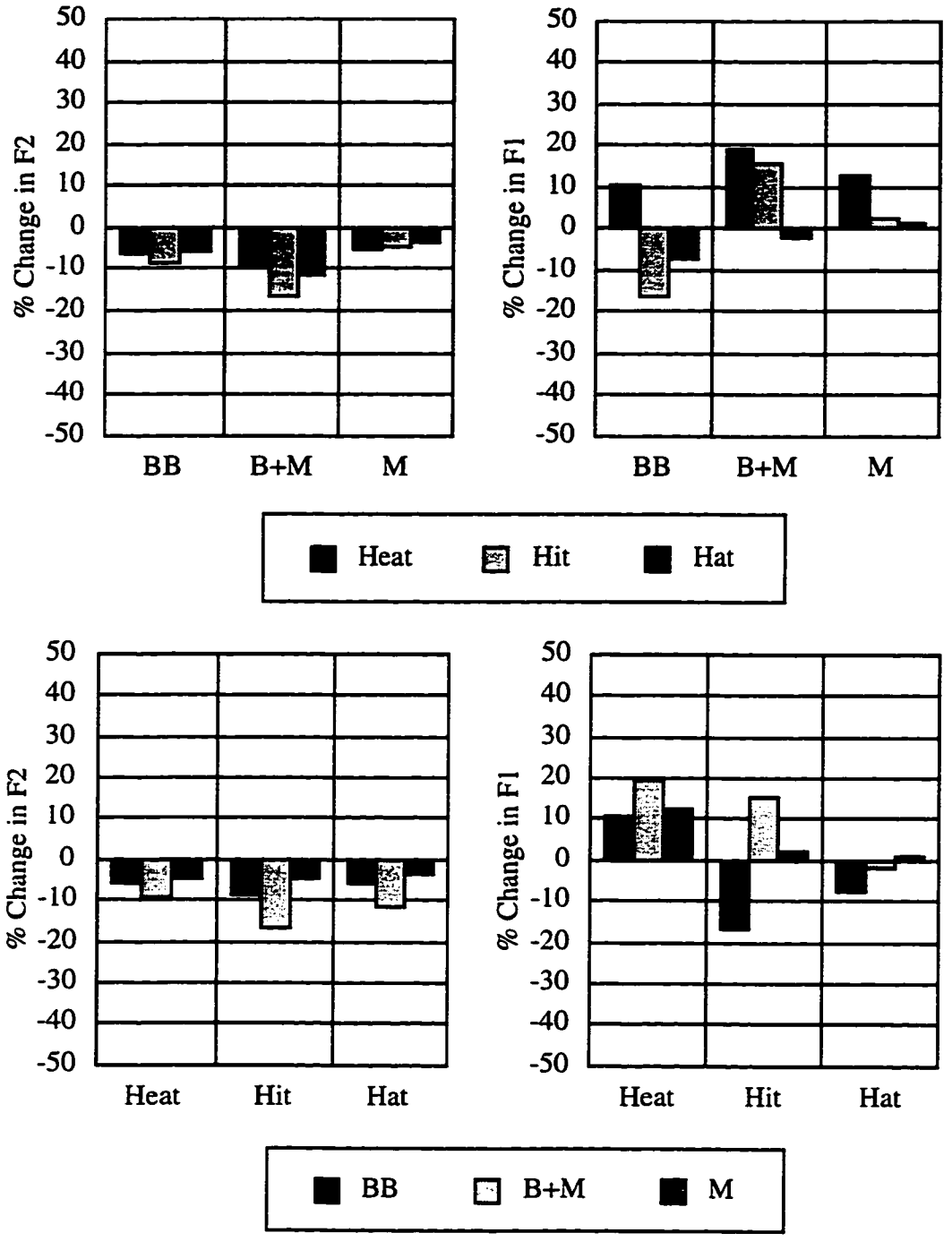


Fig. 7.8. % Change from Normal Condition in F2 and F1 in Bite-Block (BB), Bite-Block-Plus-Masking (B+M), and Masking (M) Conditions for Subject N6M

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Magnitude of Change

To determine whether any of the observed changes were statistically significant, three-way ANOVAs (for Bite Block [yes or no], Masking [yes or no], and Vowel [/i/,/I/, /ae/]) were performed for F2 and F1 for each subject separately, treating each token from each condition as a sample. Two-way ANOVAs were also performed for the standard deviation of F2 and F1 for each subject separately, using the twelve standard deviation values from three vowels in four conditions as the raw data. Three-way ANOVAs could not be performed because each cell had only one value. Thus the analyses were collapsed across one dimension, to perform two-way ANOVAs (BB x M; BB x V; and M x V). All F tables for all of the following reported results may be found for each subject with normal hearing (N1-N6) as Appendices C1-C6, respectively.

F2

Table 7.16 displays, in summary, the statistically significant changes in F2 frequency and F2 variability found for each individual subject. A highly significant ($p<.01$) main effect of bite block for F2 was revealed for every adult with normal hearing.

A significant main effect of masking for F2 was shown by five of six subjects. For four of these individuals, findings were significant at the $p<.01$ level.

No significant changes in variability of F2 were seen, as a result of test conditions, for any subject. In the case of one individual (N5M), a main effect of vowel was revealed. Post Hoc Tukey HSD Tests of differences between mean standard deviations of F2 were performed on the two vowels for which there were data. Collapsed across conditions, F2 was more variable for hit (Mean SD = 61.06) than hat (Mean SD = 32.31), $p=0.0248$).

No interaction of bite-block and masking effects, collapsed across vowels, was revealed for any subject. It will be seen in a subsequent section of this chapter, "Change Relative to Vowel Target," that the effect on F2 of either of the conditions was modified by the effect of the vowel target.

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Table 7.16.--Summary of Significant Changes in F2 for Individual Adults with Normal Hearing

Significant Changes in F2						
	N1M	N2F	N3M	N4F	N5M	N6M
Main Effect of Bite Block	↑ ★★	↓ ★★	↓ ★★	↓ ★★	↓ ★★	↓ ★★
Main Effect of Masking	↓ ★★	↓ ★★	↓ ★★	↓ ★		↓ ★★
Main Effect of Vowel	★★	★★	★★	★★	★★	★★
Interaction of Bite Block and Masking						
Significant Changes in F2 Standard Deviation						
	N1M	N2F	N3M	N4F	N5M	N6M
Main Effect of Bite Block						
Main Effect of Masking						
Main Effect of Vowel					★	
Interaction of Bite Block and Masking						

★★=p<.01, ★=p<.05, ↑ = raised formant, ↓ = lowered formant

F1

Table 7.17 displays, in summary, the statistically significant changes in F1 frequency and F1 variability found for each individual subject. A significant (at minimum, p<.05) main effect of bite block for F1 was exhibited by four of six subjects. For two of these subjects, N1M and N2F, the effect was highly significant (p<.01).

A significant main effect of masking for F1 was also shown for all subjects. For five of six of these individuals the findings were highly significant (p<.01).

No significant changes in variability for F1 were seen as a result of test conditions for any subject, however, all subjects showed a significant main effect of vowel. For half of the subjects this finding was highly significant (p<.01). Subsequent Post Hoc Tukey HSD

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tests revealed the following pattern: F1 was most variable in hat, less so in hit, and least in heat, despite condition. Because both bite-block-by-vowel and masking-by-vowel ANOVAs were performed for the standard deviation of F1 for each subject, the post hoc results are reported for each, where they were found to reach significance for the main effect of vowel. (See Table 7.18.)

Table 7.17.--Summary of Significant Changes in F1 for Individual Adults with Normal Hearing

Significant Changes in F1						
	N1M	N2F	N3M	N4F	N5M	N6M
Main Effect of Bite Block	↑ ★★	↑ ★★	↓ ★		↓ ★	
Main Effect of Masking	↑ ★★	↑ ★	↑ ★★	↑ ★★	↑ ★★	↑ ★★
Main Effect of Vowel	★★	★★	★★	★★	★★	★★
Interaction of Bite Block and Masking	★★			★	★★	★★
Significant Changes in F1 Standard Deviation						
	N1M	N2F	N3M	N4F	N5M	N6M
Main Effect of Bite Block						
Main Effect of Masking						
Main Effect of Vowel	★★	★	★★	★★	★	★
Interaction of Bite Block and Masking						

★★=p<.01, ★=p<.05, ↑ = raised formant, ↓ = lowered formant

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Table 7.18.--Summary of Results of Post Hoc Tests of the Main Effect of Vowel for F1 Standard Deviation for Every Adult with Normal Hearing

Subject	Mean Standard Deviation of F1 (Collapsed Across Conditions)			p-value		
	Heat	Hit	Hat	Heat v. Hit	Heat v. Hat	Hit v. Hat
N1M	8.17	16.78	44.81	.6667 (BBxV)	0.0217★ (BBxV)	.0626 (BBxV)
N1M	8.17	16.78	44.81	.4329 (MxV)	0.0034★★ (MxV)	0.0120★ (MxV)
N2F	26.65	N/A	45.90	N/A	0.0104★ (BBxV)	N/A
N3M	18.64	39.60	44.68	0.0024★★ (BBxV)	0.0009★★ (BBxV)	.3709 (BBxV)
N3M	18.64	39.60	44.68	0.0042★★ MxV)	0.0015★★ (MxV)	0.4436 (MxV)
N4F	28.87	42.18	94.35	.3148 (BBxV)	0.0007★★ (BBxV)	0.0020★★ (BBxV)
N4F	28.87	42.18	94.35	.4965 (MxV)	0.0027★★ (MxV)	0.0081★★ (MxV)
N5M	N/A	19.01	37.12	N/A	N/A	0.0189★ (BBxV)
N6M	14.24	29.73	38.46	.0995(BBxV)	0.0180★ (BBxV)	.3895 (BBxV)
N6M	14.24	29.73	38.46	.1197 (MxV)	0.0232★ (MxV)	.4269 (MxV)

★★=p<.01, ★=p<.05

Collapsed across vowels, significant interactions of bite-block and masking effects for F1 were shown for four of six subjects, three of which were highly significant (p<.01).

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Table 7.19 displays a summary of Post Hoc Tukey HSD tests for unequal sample sizes that revealed that mean F1 in the normal condition was significantly different from that in the bite-block condition in two of those four subjects ($p<.01$), whereas mean F1 in the normal condition was significantly different from that in both the bite-block-plus-masking and masking conditions for all four of those subjects (most at $p<.01$). Conditions employing masking were generally more detrimental to F1 than the bite block alone.

Table 7.19.--Summary of Post Hoc Tests of Significant Interactions of Bite-Block and Masking Effects (Collapsed Across Vowel) for Individual Adults with Normal Hearing

Significant Differences in F2						
Condition	N1M	N2F	N3M	N4F	N5M	N6M
Normal vs. Bite Block						
Normal vs. Bite Block and Masking						
Normal vs. Masking						
Masking vs. Bite Block						
Masking vs. Bite Block and Masking						
Bite Block vs. Bite Block and Masking						
Significant Differences in F1						
Condition	N1M	N2F	N3M	N4F	N5M	N6M
Normal vs. Bite Block	↑ ★★					↓ ★★
Normal vs. Bite Block and Masking	↑ ★★			↑ ★★	↑ ★★	↑ ★★
Normal vs. Masking	↑ ★★			↑ ★★	↑ ★★	↑ ★
Masking vs. Bite Block	★★			★★	★★	★★
Masking vs. Bite Block and Masking	★★				★★	★
Bite Block vs. Bite Block and Masking				★★	★★	★★

★★=$p<.01$, ★=$p<.05$, ↑ = raised formant, ↓ = lowered formant

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Change Relative to Vowel Target

In the previous section, "Magnitude of Change," discussion was given to the results of ANOVAs that examined the effect of test conditions collapsed across vowels. Those same ANOVAs also revealed condition-by-vowel interactions that will be taken up here. It will be seen, both in figures and tests of significance, that the effect of test conditions was modified by the vowel target. Simply put, some conditions affected some vowels more than others.

First, these effects have been presented graphically for each subject. Figures 7.12 - 7.23 follow. Two figures are presented per page for each of the six adults with normal hearing. The figure at the top of the page displays mean F2 and F1 values from each condition in a traditional F1-by-F2 plot of "vowel space." The figures at the bottom of each page present two panels, left and right, of plots of the standard deviation of F2 and F1, respectively. The figures display the varying effects of test condition, depending on vowel target, on both mean formant measures and the variability of production. They also reveal the profiles of articulatory adjustments by each individual.

Let us take Figures 7.12 and 7.13 for the first subject, N1M, as an example. It can be seen from the top figure that test conditions produced the fewest changes in formant frequencies for /i/, more for /I/, and most for /ae/. The close vowels, /i/ and /I/, predominantly exhibited F2 changes as a result of test conditions, whereas the open vowel /ae/ exhibited more change in F1. In the bite-block condition, this subject appeared to overcompensate, in that F2 values were a bit raised from normal, opposite to the predicted lowering effect of a bite block. However, all other conditions generally lowered F2 and raised F1 values, as predicted by computer simulation. Variability of production of F2 was unremarkable in that no obvious and consistent differences were discerned among vowels or conditions. In contrast, F1 variability was clearly least in /i/ and greatest in /ae/, despite condition. Yet, examining by condition for the vowel /ae/, it can be seen that conditions

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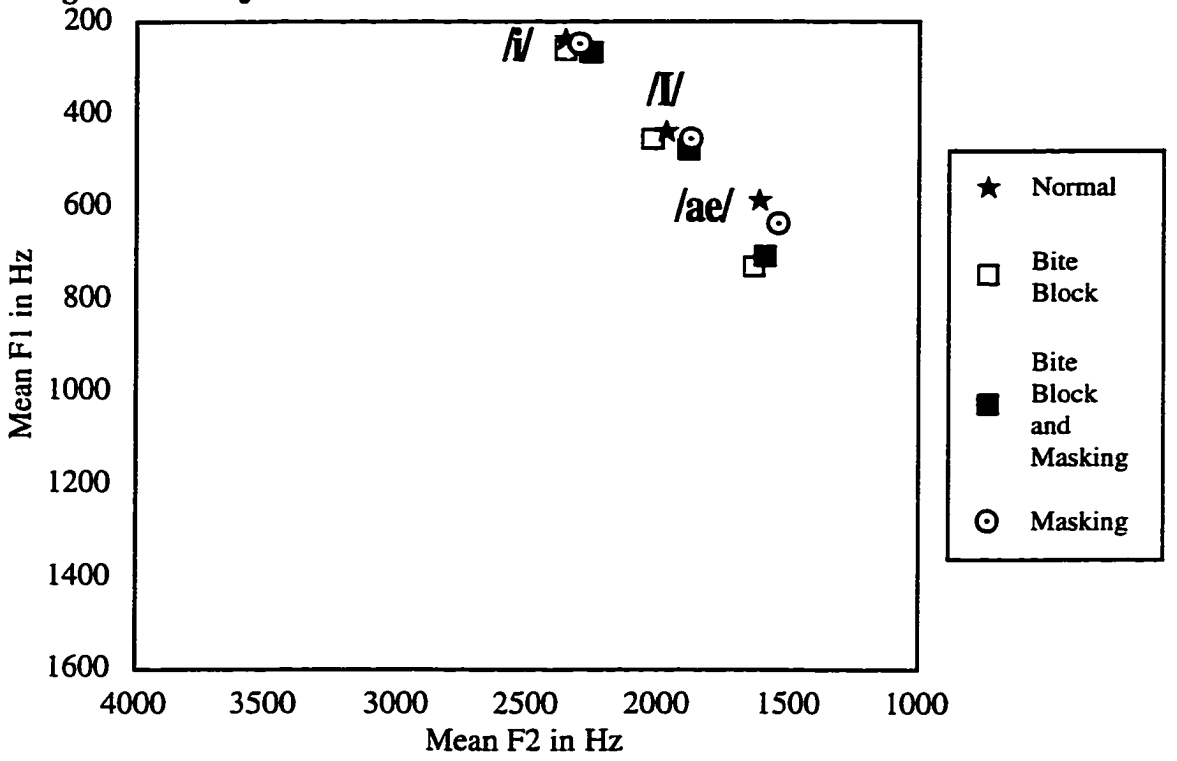
employing masking (B+M and M) resulted in more variability of production than conditions without masking, though these differences were not found to be significant.

While the figures reveal much about individual differences in the effect of test conditions and articulatory adjustments, one must return to the statistical tests of significance in order to make useful generalizations about conditions that changed the production of some vowels more than others, for most individuals.

Significant interactions of bite-block and vowel effects, masking and vowel effects, and bite-block, masking and vowel effects were revealed for most subjects for F2 and F1. Summary tables are presented below to consolidate the detailed results. The reader will remember from earlier tables that no hit data were obtained from N2F and no heat data were obtained from N5M, so N/A will appear in parts of the tables where those data are missing. All F tables for all of the following reported results may be found for each subject with normal hearing (N1-N6) as Appendices C1-C6, respectively.

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Fig. 7.9. Subject N1M: Mean F1 x F2 Plot of Vowels in Each Condition



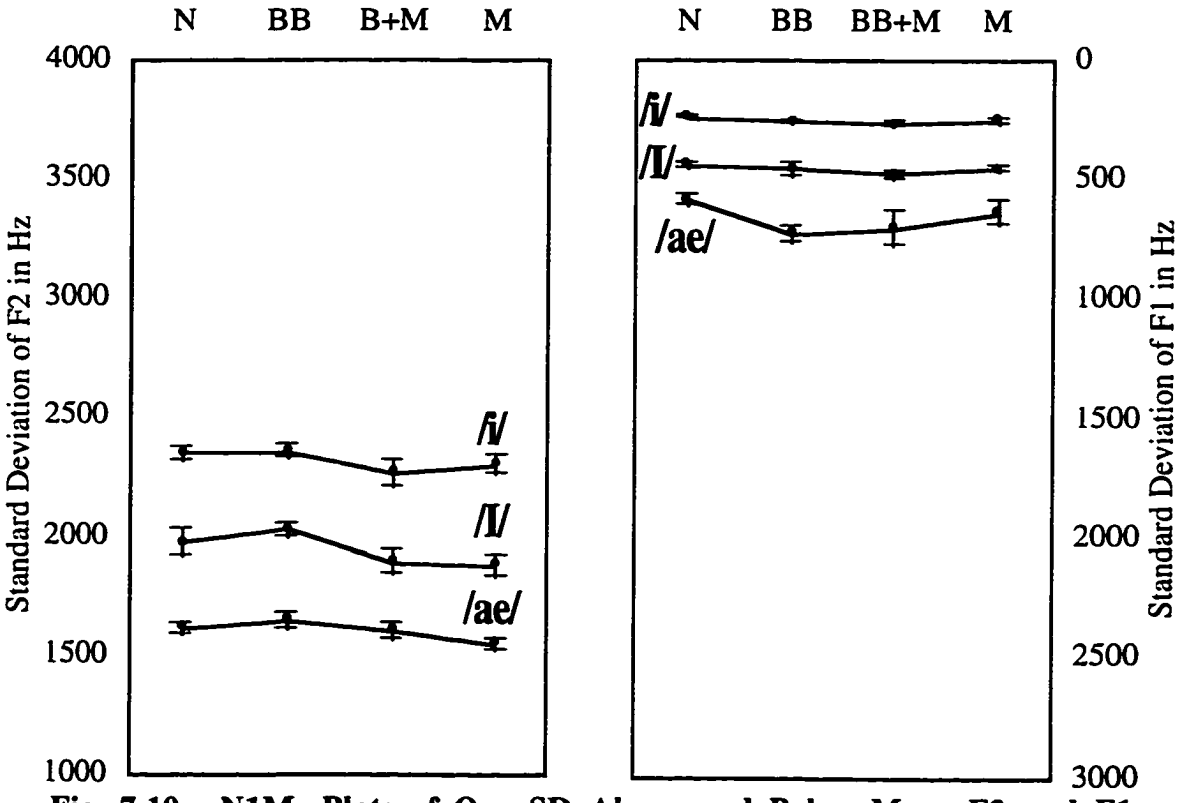
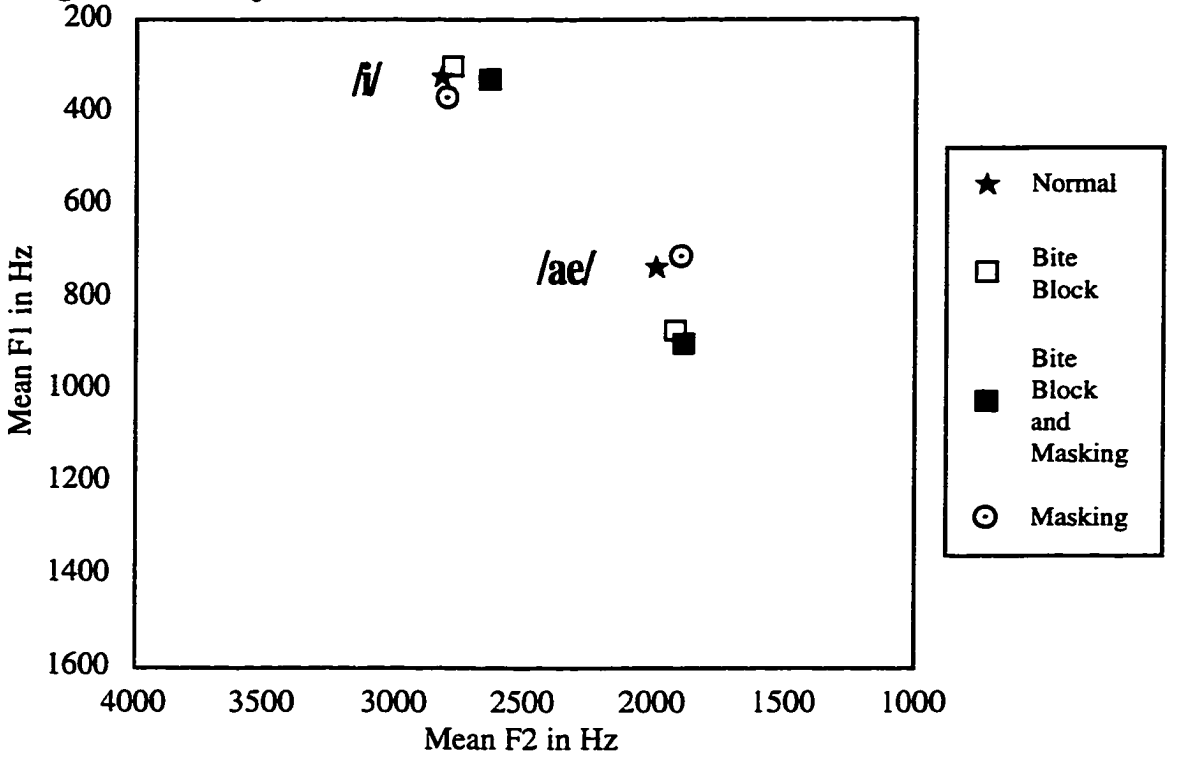


Fig. 7.10. N1M: Plots of One SD Above and Below Mean F2 and F1

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Fig. 7.11. Subject N2F: Mean F1 x F2 Plot of Vowels in Each Condition



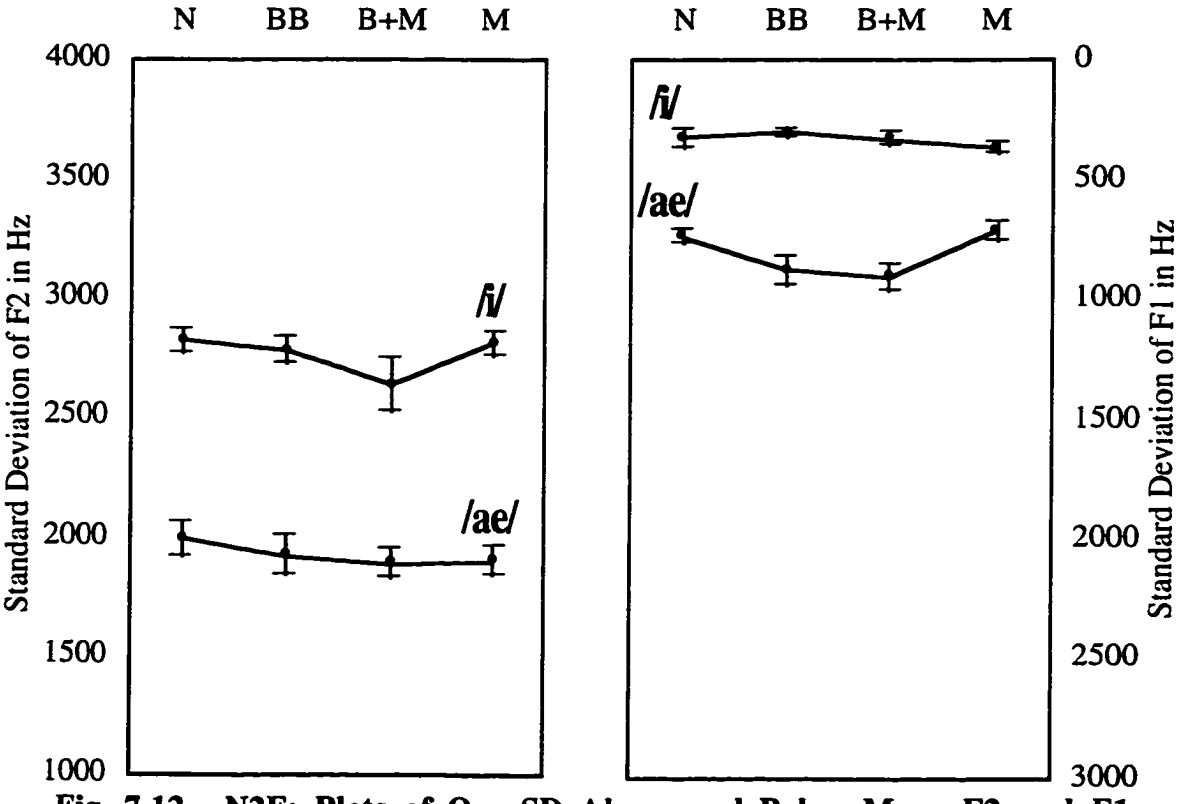
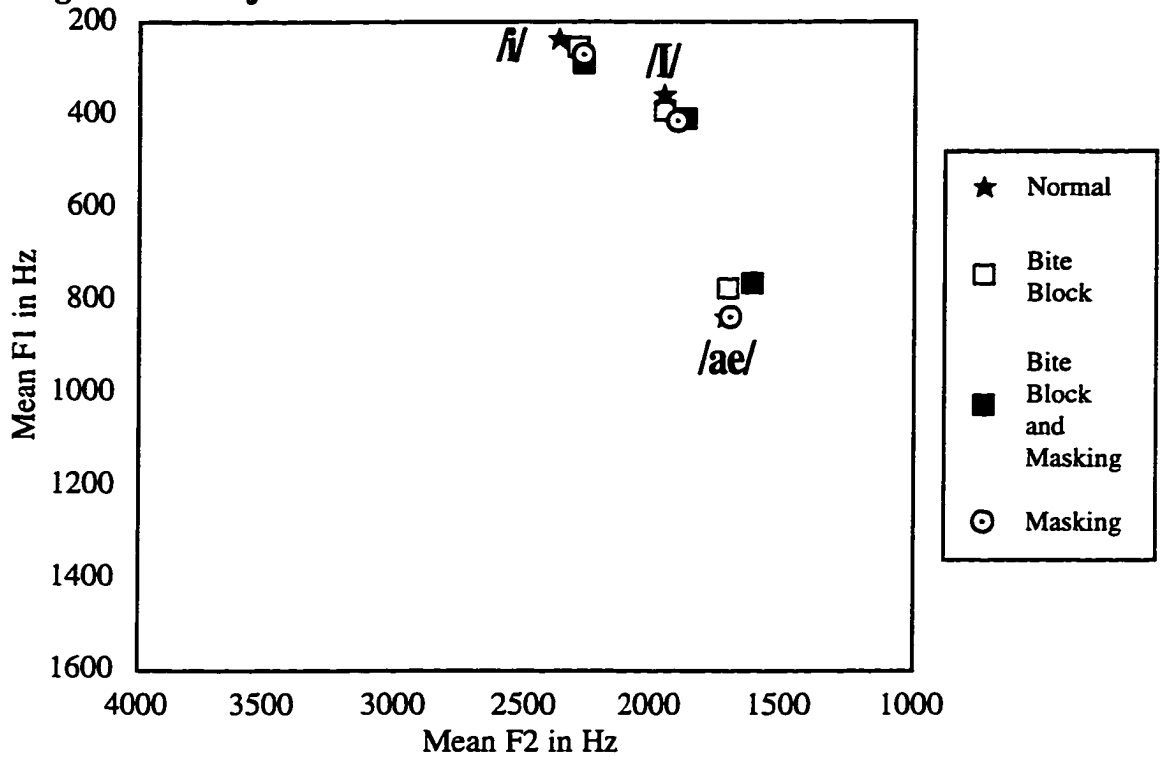


Fig. 7.12. N2F: Plots of One SD Above and Below Mean F2 and F1

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Fig. 7.13. Subject N3M: Mean F1 x F2 Plot of Vowels in Each Condition



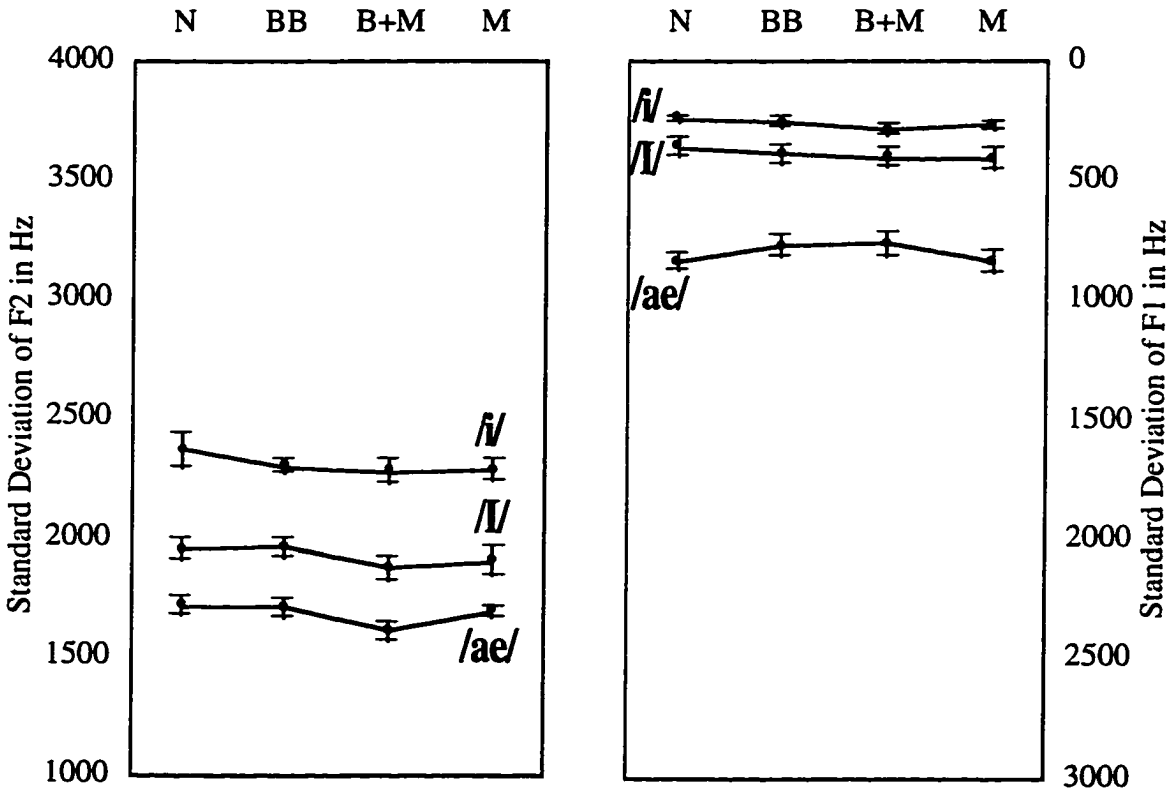
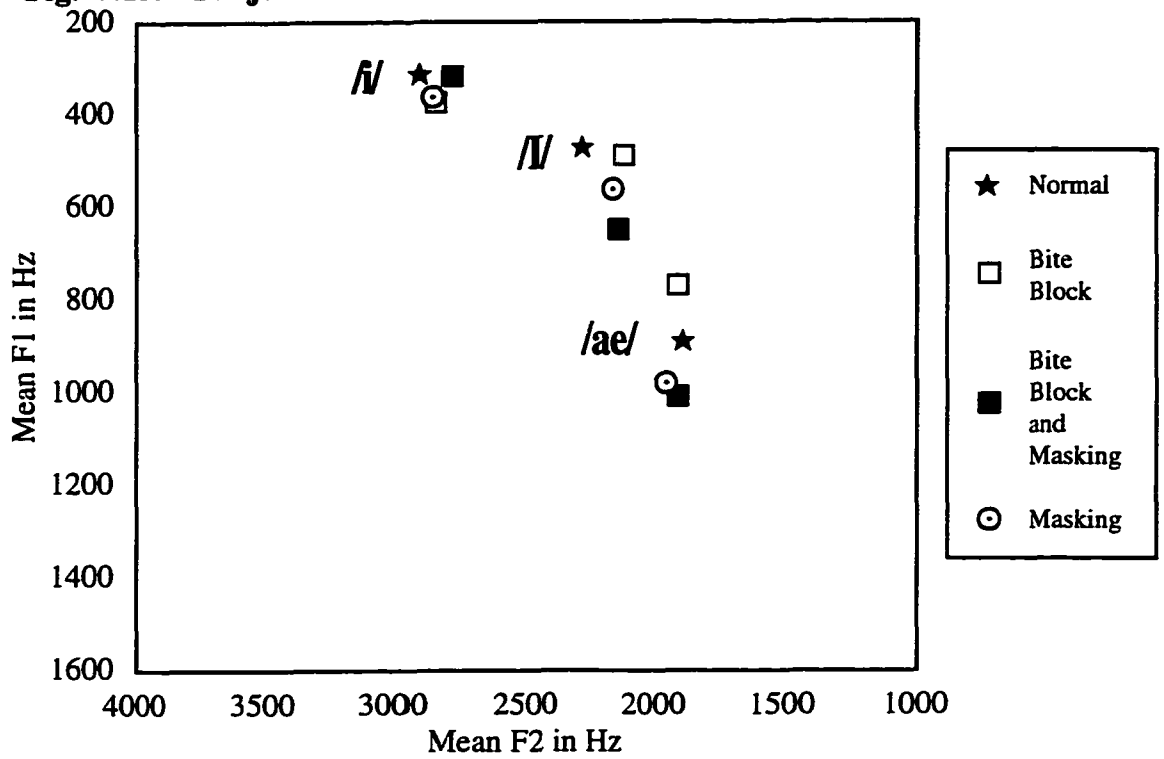


Fig. 7.14. N3M: Plots of One SD Above and Below Mean F2 and F1

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Fig. 7.15. Subject N4F: Mean F1 x F2 Plot of Vowels in Each Condition



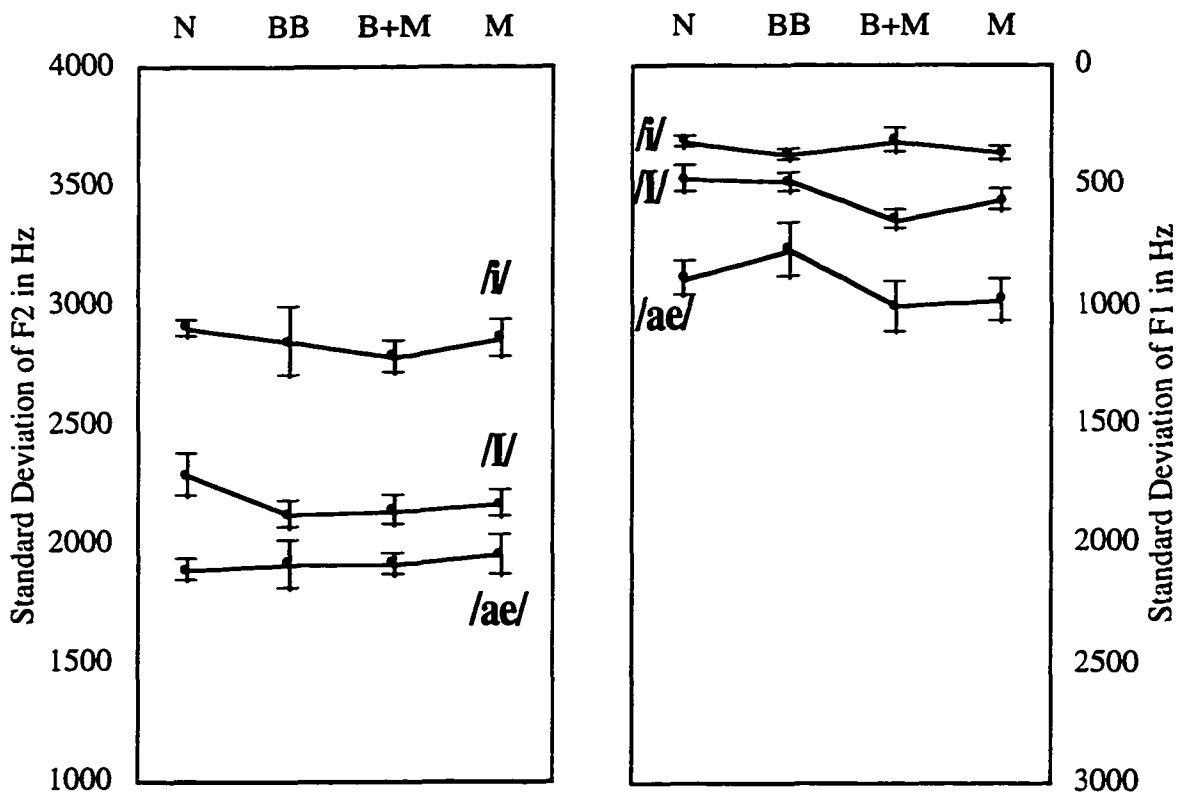
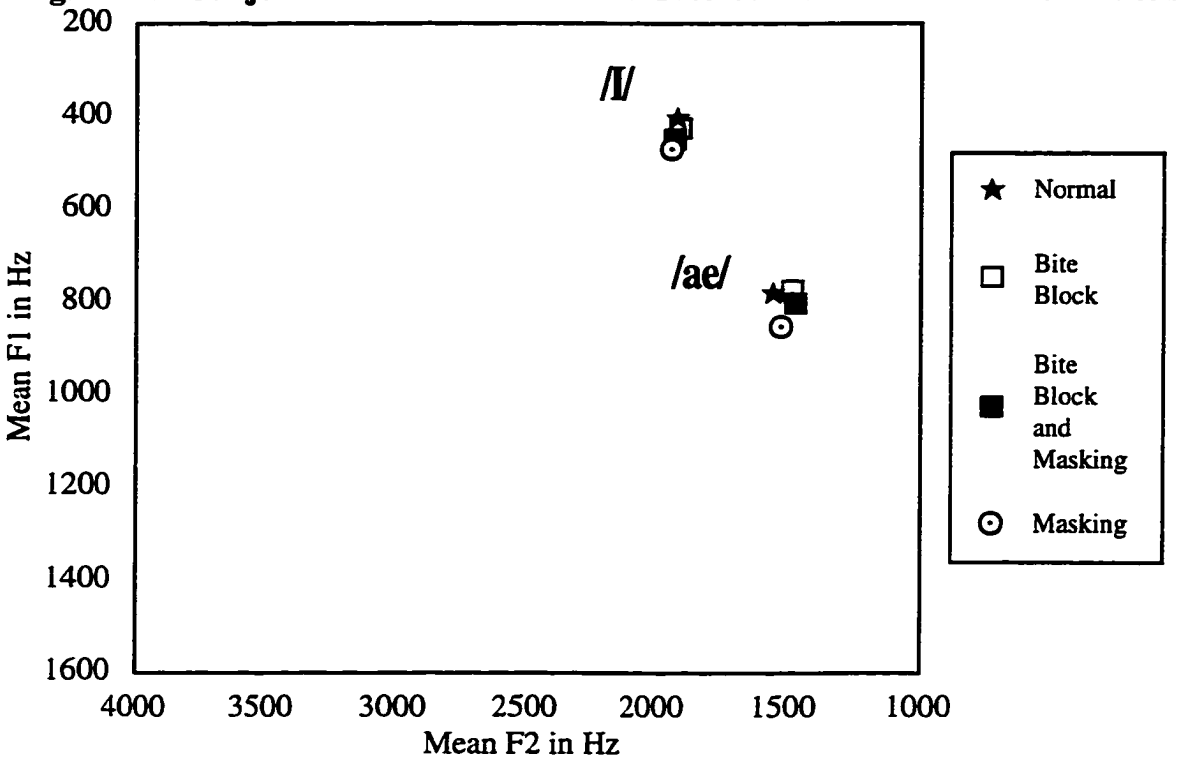


Fig. 7.16. N4F: Plots of One SD Above and Below Mean F2 and F1

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Fig. 7.17. Subject N5M: Mean F1 x F2 Plot of Vowels in Each Condition



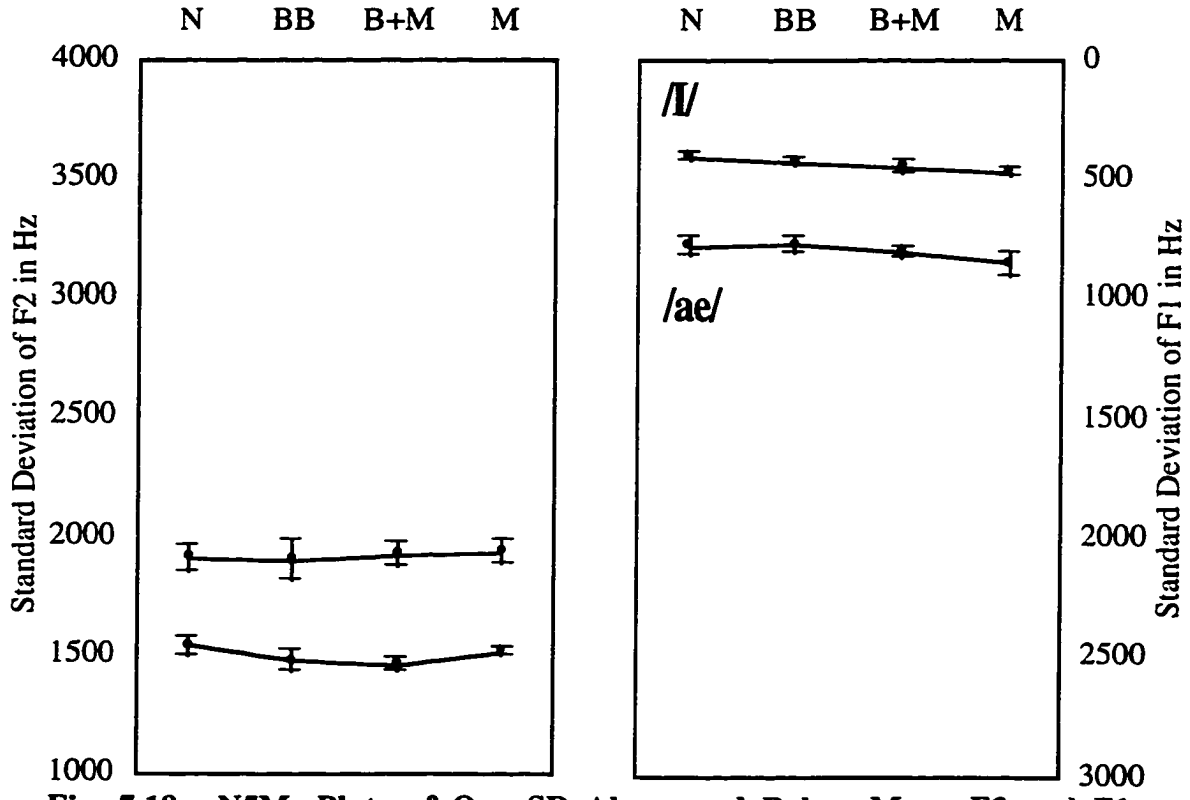
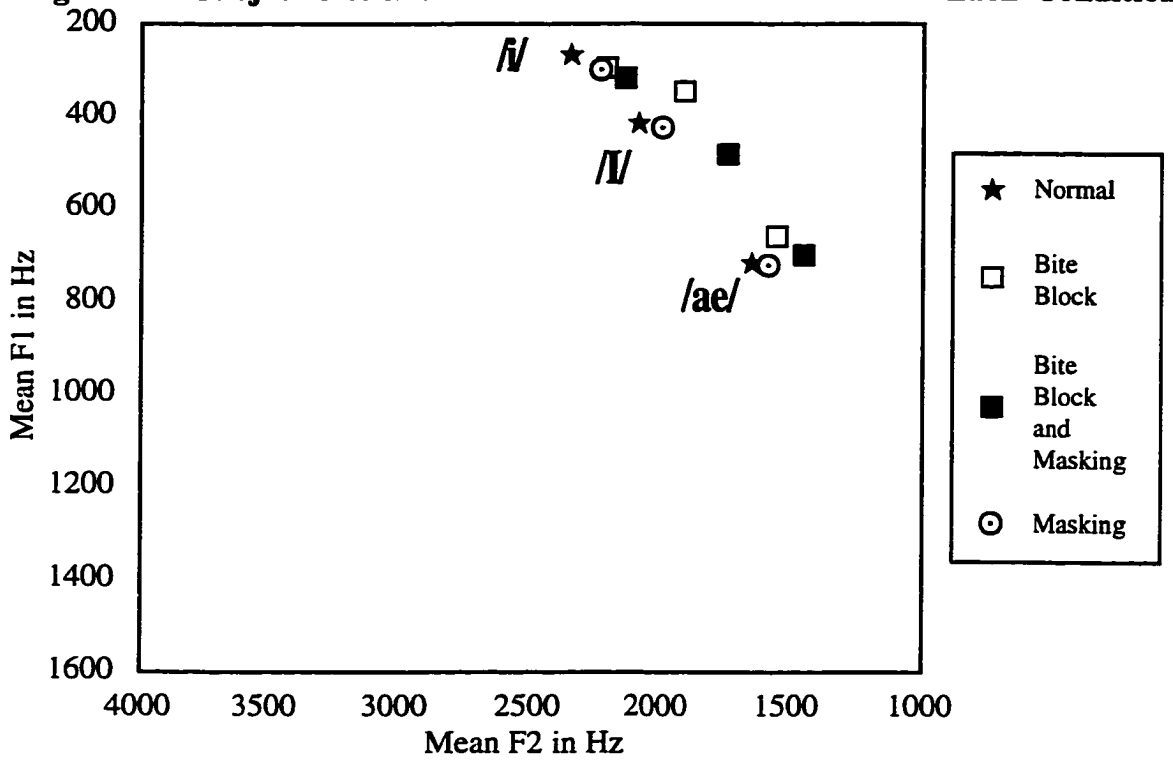


Fig. 7.18. N5M: Plots of One SD Above and Below Mean F2 and F1

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Fig. 7.19. Subject N6M: Mean F1 x F2 Plot of Vowels in Each Condition



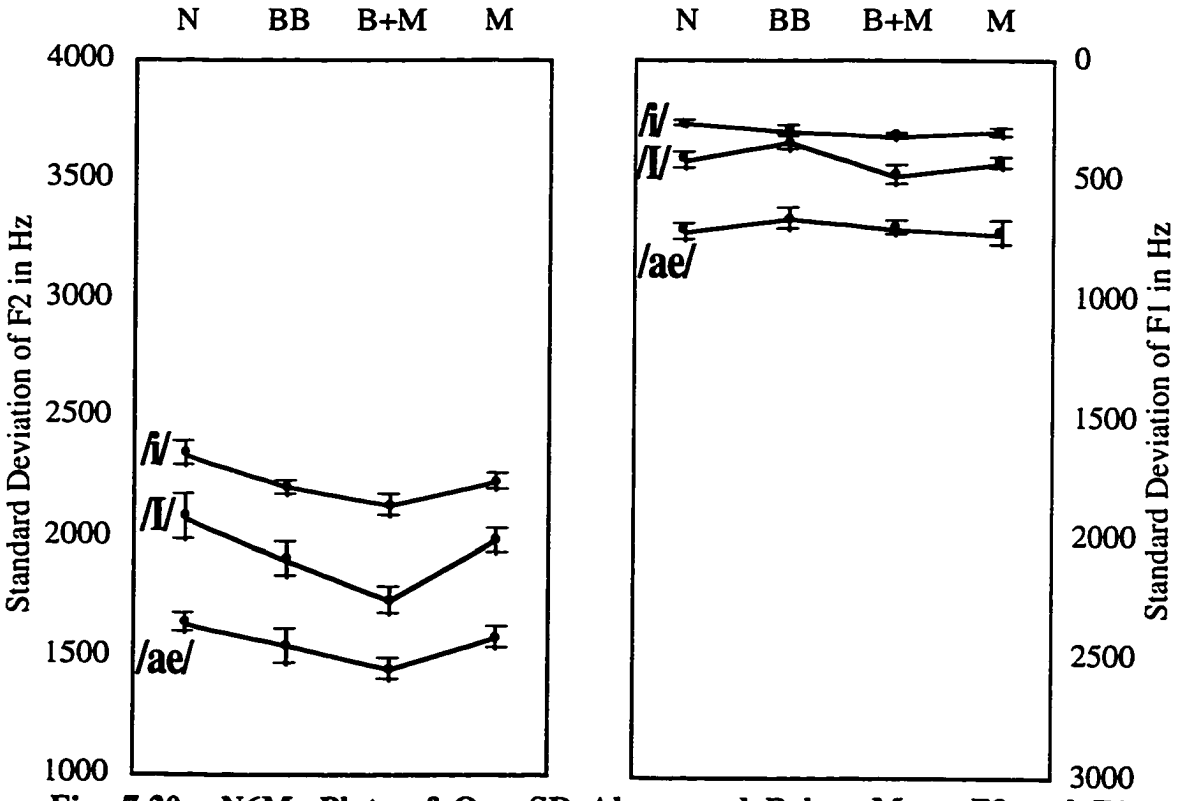


Fig. 7.20. N6M: Plots of One SD Above and Below Mean F2 and F1

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In order to distinguish patterns and trends from the details of the results, discussion will focus on findings that were obtained from a majority of individual subjects. The words "most of" and "the majority of" subjects will be used when similar results were obtained from three subjects of five, where data were missing for one subject, or four of six subjects, where all data were available.

F2

Changes in F2, as a result of interactions of test condition and vowel target, were exhibited by a majority of subjects. Significant interactions and subsequent post hoc tests are summarized in Tables 7.20, 7.22, 7.23, and 7.24.

Table 7.20 shows that a significant interaction (a minimum of $p<.05$) of bite-block and vowel effects was found for five of six subjects. However, Post Hoc Tukey HSD tests for unequal sample sizes, summarized in Table 7.22, revealed individual variability rather than a predominant pattern of interaction, wherein bite-block effects were modified by a particular vowel target.

Table 7.20 displays a significant interaction (a minimum of $p<.05$) of masking and vowel effects in four of six subjects, however, Post Hoc Tukey HSD tests for unequal sample sizes, summarized in Table 7.23, showed that conditions employing masking affected productions by only two subjects, N1M and N6M. (The bite-block conditions had also resulted in significant changes in all vowels produced by N6M. See Table 7.22.)

Table 7.20 shows a significant (minimum of $p<.05$) interaction of bite-block, masking and vowel effects in five of six subjects. Post Hoc Tukey HSD tests for unequal sample sizes are summarized in Table 7.24.

For heat, F2 was significantly ($p<.01$) different from normal in the bite-block-plus-masking condition for all subjects for whom there were data. It should also be noted that F2 in the bite-block condition was significantly (a minimum of $p<.05$) different from the bite-block-plus-masking condition for a majority of subjects, suggesting that the the

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combination of effects was more detrimental to heat F2 production than bite block alone (cf Figures 7.9, 7.11, 7.15 and 7.19).

Table 7.20.--Summary of Significant Interactions of Effects on F2 in Individual Adults with Normal Hearing

Significant Interactions of Effects on F2						
	N1M	N2F	N3M	N4F	N5M	N6M
Interaction of Bite Block and Vowel	★★	★		★★	★★	★★
Interaction of Masking and Vowel	★★			★★	★	★
Interaction of Bite Block, Masking, and Vowel	★	★★	★★	★★		★★
Significant Interactions of Effects on F2 Standard Deviation						
	N1M	N2F	N3M	N4F	N5M	N6M
Interaction of Bite Block and Vowel						
Interaction of Masking and Vowel						

★★=p<.01, ★=p<.05

Of the three vowels, hit showed the most significant differences (a minimum of p<.05) in F2 between normal and test conditions. F2 in every test condition was highly significantly different (p<.01) from normal condition in a majority of subjects. Examining the significant differences among test conditions did not reveal an overall pattern, but highlighted individual differences in articulatory adjustments. For N1M and N3M, the effect of bite block on F2 in hit was distinct from the two conditions employing masking noise (cf Figure 7.9 and 7.13). N4F, on the other hand, seemed to be affected by test conditions all quite equally (cf Figure 7.15). For N6M, masking, bite-block and bite-block-plus-masking conditions produced progressively greater changes in hit F2 from normal (cf Figure 7.19).

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Finally, F2 in hat was susceptible to change as a result of masking conditions. Masking most lowered F2 in N1M (cf Figure 7.9). Both masking and bite-block-plus-masking most lowered F2 in N2F (cf Figure 7.11). The bite-block-plus-masking most lowered F2 in N3M (cf Figure 7.13) and N6M (cf Figure 7.19).

Individual responses to the test conditions varied widely from very accurate F2 articulatory compensation by subject N5M (cf Figure 7.17) to less successful F2 adjustments by N6M (cf Figure 7.19).

No significant interaction of bite-block and vowel, masking and vowel, or bite-block, masking and vowel effects was shown for F2 variability. (See Table 7.20.)

F1

Changes in F1, as a result of interactions of test condition and vowel target, were exhibited by a majority of subjects. Significant interactions and subsequent post hoc tests are summarized in Tables 7.21, 7.22, 7.23, and 7.25.

Table 7.21 shows that a significant interaction (a minimum of $p<.05$) of bite-block and vowel effects was found for all subjects. Post Hoc Tukey HSD tests for unequal sample sizes are summarized in Table 7.22. All subjects showed significant (a minimum of $p<.05$) differences in F1 for hat, between conditions where a bite block was and was not used. In contrast, the higher vowels showed little effect of the bite block on F1.

Table 7.21 displays a significant interaction (a minimum of $p<.05$) of masking and vowel effects in four of six subjects. Post Hoc Tukey HSD tests for unequal sample sizes, summarized in Table 7.23, revealed that the effect of the masking-by-vowel interaction is the reverse of that seen for the bite-block-by-vowel interaction. That is, for a majority of subjects there were highly significant ($p<.01$) differences in F1 for /i/ and /I/ between conditions where masking was and was not used. In contrast, /ae/ showed little effect of masking on F1.

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Table 7.21.--Summary of Significant Interactions of Effects on F1 in Individual Adults with Normal Hearing

Significant Interactions of Effects on F1						
	N1M	N2F	N3M	N4F	N5M	N6M
Interaction of Bite Block and Vowel	★★	★★	★★	★★	★	★★
Interaction of Masking and Vowel		★	★★	★★		★★
Interaction of Bite Block, Masking, and Vowel	★★	★		★★		★★
Significant Interactions of Effects on F1 Standard Deviation						
	N1M	N2F	N3M	N4F	N5M	N6M
Interaction of Bite Block and Vowel		★				
Interaction of Masking and Vowel	★					

★★=p<.01; ★=p<.05

Table 7.21 shows a significant (minimum of p<.05) interaction of bite-block, masking and vowel effects in four of six subjects. Post Hoc Tukey HSD tests for unequal sample sizes are summarized in Table 7.25. Heat F1 was barely affected by test conditions. F1 changes were seen more frequently in /I/, but only the bite-block-plus-masking condition resulted in a significant (a minimum of p<.05) difference from the normal condition in a majority of subjects. One of the women, N4F, and one of the men, N6M, exhibited less successful adjustments for test conditions with this vowel (cf Figure 7.15 and Figure 7.19, respectively).

In contrast, F1 for hat was particularly affected by test conditions. Table 7.25 displays the individual differences in articulatory adjustments. For N1M and N2F, the effect of conditions employing a bite block produced larger F1 changes from normal than did masking noise alone (cf Figures 7.9 and 7.11). For N4F the effect of the bite block

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alone was essentially equal to and opposite of the effect of conditions employing masking noise. Each resulted in rather equivalent amounts of F1 change, but in opposite directions (cf Figure 7.15). For N6M the bite-block condition lowered F1 more than did conditions employing masking (cf Figure 7.19).

Most subjects showed no significant interaction of bite-block and vowel, masking and vowel, or bite-block, masking and vowel effects on F1 variability. (See Table 7.21.)

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Table 7.22.--Summary of Post Hoc Tests of Significant Interactions of Bite-Block and Vowel Effects (Collapsed Across Masking) for Individual Adults with Normal Hearing

Significant Differences in F2						
Condition and Vowel	N1M	N2F	N3M	N4F	N5M	N6M
No Bite-Block "heat" vs. Bite-Block "heat"		↓ ★★		↓ ★★	N/A	↓ ★★
No Bite-Block "hit" vs. Bite-Block "hit"	↑ ★★	N/A		↓ ★★		↓ ★★
No Bite-Block "hat" vs. Bite-Block "hat"	↑ ★★				↓ ★★	↓ ★★
Significant Differences in F1						
Condition and Vowel	N1M	N2F	N3M	N4F	N5M	N6M
No Bite-Block "heat" vs. Bite-Block "heat"		↓ ★			N/A	↑ ★
No Bite-Block "hit" vs. Bite-Block "hit"		N/A		↑ ★		
No Bite-Block "hat" vs. Bite-Block "hat"	↑ ★★	↑ ★★	↓ ★★	↓ ★	↓ ★★	↓ ★★

Table 7.23.--Summary of Post Hoc Tests of Significant Interactions of Masking and Vowel Effects (Collapsed Across Bite Block) for Individual Adults with Normal Hearing

Significant Differences in F2						
Condition and Vowel	N1M	N2F	N3M	N4F	N5M	N6M
No Masking "heat" vs. Masking "heat"	↓ ★★				N/A	↓ ★★
No Masking "hit" vs. Masking "hit"	↓ ★★	N/A				↓ ★★
No Masking "hat" vs. Masking "hat"	↓ ★★					↓ ★★
Significant Differences in F1						
Condition and Vowel	N1M	N2F	N3M	N4F	N5M	N6M
No Masking "heat" vs. Masking "heat"		↑ ★★	↑ ★★		N/A	↑ ★★
No Masking "hit" vs. Masking "hit"		N/A	↑ ★★	↑ ★★		↑ ★★
No Masking "hat" vs. Masking "hat"				↑ ★★		↑ ★

★★=p<.01, ★=p<.05, ↑ = raised formant, ↓ = lowered formant

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Table 7.24.--Summary of Post Hoc Tests of Significant Interactions of Bite-Block, Masking, and Vowel Effects on F2 for Individual Adults with Normal Hearing

Significant Differences in F2						
Condition and Vowel	N1M	N2F	N3M	N4F	N5M	N6M
Normal "heat" vs. Bite-Block "heat"			★★		N/A	★★
Normal "heat" vs. Bite-Block-plus-Masking "heat"	★★	★★	★★	★★	N/A	★★
Normal "heat" vs. Masking "heat"			★★		N/A	★★
Masking "heat" vs. Bite-Block "heat"					N/A	
Masking "heat" vs. Bite-Block-plus-Masking "heat"		★★			N/A	★★
Bite Block "heat" vs. Bite-Block-plus-Masking "heat"	★★	★★			N/A	★
Normal "hit" vs. Bite-Block "hit"	★★	N/A		★★		★★
Normal "hit" vs. Bite-Block-plus-Masking "hit"	★★	N/A	★★	★★		★★
Normal "hit" vs. Masking "hit"	★★	N/A		★★		★★
Masking "hit" vs. Bite-Block "hit"	★★	N/A	★			★★
Masking "hit" vs. Bite-Block-plus-Masking "hit"		N/A				★★
Bite Block "hit" vs. Bite-Block-plus-Masking "hit"	★★	N/A	★★			★★
Normal "hat" vs. Bite-Block "hat"						★★
Normal "hat" vs. Bite-Block-plus-Masking "hat"		★★	★★			★★
Normal "hat" vs. Masking "hat"	★★	★				
Masking "hat" vs. Bite-Block "hat"	★★					
Masking "hat" vs. Bite-Block-plus-Masking "hat"	★★		★★			★★
Bite Block "hat" vs. Bite-Block-plus-Masking "hat"			★★			★★

★★=p<.01, ★=p<.05, direction of change illustrated in Figures 7.21-7.23

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Table 7.25.--Summary of Post Hoc Tests of Significant Interactions of Bite-Block, Masking, and Vowel Effects on F1 for Individual Adults with Normal Hearing

Significant Differences in F1						
Condition and Vowel	N1M	N2F	N3M	N4F	N5M	N6M
Normal "heat" vs. Bite-Block "heat"					N/A	
Normal "heat" vs. Bite-Block-plus-Masking "heat"					N/A	★★
Normal "heat" vs. Masking "heat"					N/A	
Masking "heat" vs. Bite-Block "heat"		★★			N/A	
Masking "heat" vs. Bite-Block-plus-Masking "heat"					N/A	
Bite Block "heat" vs. Bite-Block-plus-Masking "heat"					N/A	
Normal "hit" vs. Bite-Block "hit"		N/A				★★
Normal "hit" vs. Bite-Block-plus-Masking "hit"	★	N/A		★★		★★
Normal "hit" vs. Masking "hit"		N/A		★★		
Masking "hit" vs. Bite-Block "hit"		N/A		★		★★
Masking "hit" vs. Bite-Block-plus-Masking "hit"		N/A		★★		★★
Bite Block "hit" vs. Bite-Block-plus-Masking "hit"		N/A		★★		★★
Normal "hat" vs. Bite-Block "hat"	★★	★★		★★		★★
Normal "hat" vs. Bite-Block-plus-Masking "hat"	★★	★★		★★		
Normal "hat" vs. Masking "hat"	★★			★★		
Masking "hat" vs. Bite-Block "hat"	★★	★★		★★		★★
Masking "hat" vs. Bite-Block-plus-Masking "hat"	★★	★★				
Bite Block "hat" vs. Bite-Block-plus-Masking "hat"				★★		★

★★=p<.01, ★=p<.05, direction of change illustrated in Figures 7.21-7.23

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Summary

In this chapter, and all subsequent results chapters, summary tables like Tables 7.26 - 7.29 below will be used to consolidate, compare, and contrast bite-block, masking, and bite-block-plus-masking effects on all dependent variables, to show patterns revealed by the majority of individual talkers within each subject group. Columns for results from subsequent chapters appear in gray now.

The data from individual talkers revealed that:

A. the bite-block condition lowered F2 in a majority of speakers, the direction of change predicted by computer simulation. (See Table 7.26.) Every speaker showed a significant main effect of bite block. Most subjects also showed a significant bite-block-by-vowel interaction, but there was no consistent pattern across subjects of test condition effects on any one vowel. The bite-block condition raised F1 for /i/ and /I/, as predicted by computer simulation. F1 was lowered for /ae/. Computer simulation predicted that F1 may be either raised or lowered, depending on whether the bite block creates a greater-than-normal or less-than-normal interincisor distance, respectively. A majority of speakers displayed a main effect of bite block on F1 and all subjects exhibited a significant bite-block-by-vowel interaction: /i/ and /I/ showed little effect while all speakers showed significant differences between bite-block and non-bite-block conditions of hat.

B. the masking condition resulted in changes in F2 in the same direction as the bite-block condition. (See Table 7.27.) A majority of speakers showed a lowered F2 and a significant main effect of masking. They also showed a significant masking-by-vowel interaction. While no overall patterns of change were revealed, two subjects were particularly affected by masking for all vowels. Masking raised F1 for a majority of speakers. This was the same direction as the bite-block effect for /i/ and /I/. However, the bite-block had lowered /ae/ F1. All subjects exhibited a significant main effect of masking on F1. A majority of the subjects also showed a significant masking-by-vowel

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interaction: there was little effect on hat, while /i/ and /I/ showed significant differences between masking and non-masking conditions.

C. the bite-block-plus-masking condition also lowered F2, but there was no significant interaction of bite-block and masking effects for F2. (See Table 7.28.) However, a majority of subjects showed a significant bite-block-by-masking-by-vowel interaction for F2. Figures 7.21 - 7.23 provide an overview of direction and magnitude of formant changes in every individual adult with normal hearing. Where subjects exhibited a significant interaction of bite block, masking and vowel, post hoc tests were conducted for differences. (See Tables 7.20, 7.21, 7.24, and 7.25.) Those post hoc tests that showed significant differences between normal and test conditions are identified by stars in Figures 7.21 - 7.23. Heat F2 was changed more by the bite-block-plus-masking condition than by either bite-block or masking alone (Figure 7.21). Hit F2 showed no overall pattern of change (Figure 7.22). Hat F2 was most changed by the bite-block-plus-masking condition (Figure 7.23). A majority of subjects exhibited a raised F1 and a significant bite-block-by-masking interaction: masking and the bite-block-plus-masking condition resulted in larger F1 changes than bite block alone. Most of the subjects also showed a significant bite-block-by-masking-by-vowel interaction. Heat F1 was little affected. Hit F1 was particularly affected by the bite-block-plus-masking condition in subjects N4F and N6M. Hat F1 was affected more by bite-block and bite-block-plus-masking conditions than by masking alone.

D. test conditions did not result in systematic changes in variability of production for either F2 or F1. (See Table 7.29.) However, all subjects showed a significant main effect of vowel for F1. F1 was most variable in hat, less so in hit, and least in heat, collapsed across condition.

E. individual subjects varied in their ability to compensate in test conditions.

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Table 7.26.--Summary of Bite-Block Effects on F2 and F1 for the Majority of Individual Subjects

	Adults with Normal Hearing	Children with Normal Hearing	Adults with Profound Hearing Loss	Adults with Severe Hearing Loss
F2 Direction of Change: heat hit hat	 lowered lowered lowered			
Range of % Change	.23 - 16.58%			
Main Effect of Bite Block	★★(all)			
BB-by-Vowel Interaction	★/★★			
Details of Interaction:	individual variation in affected vowel targets			
F1 Direction of Change: heat hit hat	 raised raised lowered			
Range of % Change	.38 - 24.25%			
Main Effect of Bite Block	★/★★			
BB-by-Vowel Interaction	★/★★(all)			
Details of Interaction:	<u>hat</u> most often affected			

★★=p<.01, ★=p<.05

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Table 7.27.--Summary of Masking Effects on F2 and F1 for the Majority of Individual Subjects

	Adults with Normal Hearing	Children with Normal Hearing	Adults with Profound Hearing Loss	Adults with Severe Hearing Loss
F2 Direction of Change: heat hit hat	 lowered lowered lowered			
Range of % Change	.43 - 5.4%			
Main Effect of Masking	★/★★			
M-by-Vowel Interaction	★/★★			
Details of Interaction:	N1M and N6M particularly affected by masking for all vowels			
F1 Direction of Change: heat hit hat	 raised raised raised			
Range of % Change	.22 - 18.8%			
Main Effect of Masking	★/★★(all)			
M-by-Vowel Interaction	★/★★			
Details of Interaction:	heat and hit most often affected			

★★=p<.01, ★=p<.05

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Table 7.28.--Summary of Bite-Block-plus-Masking Effects on F2 and F1 for the Majority of Individual Subjects

	Adults with Normal Hearing	Children with Normal Hearing	Adults with Profound Hearing Loss	Adults with Severe Hearing Loss
F2 Direction of Change: heat hit hat	 lowered lowered lowered			
Range of % Change	.66 - 16.71%			
Interaction of BB and M				
Interaction of BB and M and Vowel	★/★★			
Details of Interactions: heat hit hat	 affected more by B+M than by BB or M alone no overall pattern affected more by B+M than by BB or M alone			
F1 Direction of Change: heat hit hat	 raised raised raised			
Range of % Change	.44 - 36.67%			
Interaction of BB and M	★/★★			
Interaction of BB and M and Vowel	★/★★			
Details of Interactions: in general heat hit hat	 M and B+M more detrimental than BB alone little effect B+M detrimental for N4F and N6M BB and B+M more detrimental than masking alone			

★★=p<.01, ★=p<.05

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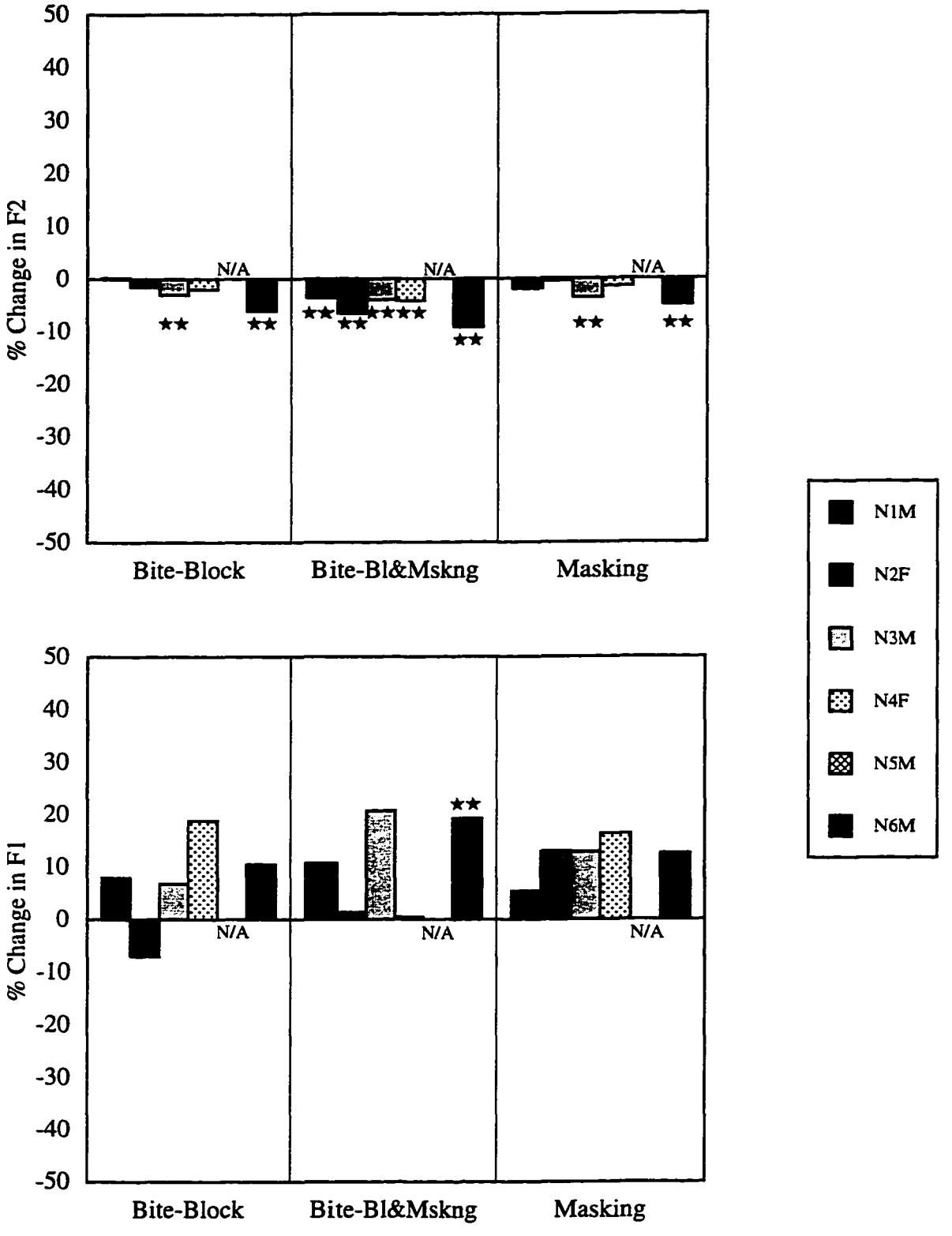
Table 7.29.--Summary of All Test Effects on F2 and F1 Variability for the Majority of Individual Subjects

	Adults with Normal Hearing	Children with Normal Hearing	Adults with Profound Hearing Loss	Adults with Severe Hearing Loss
Main Effect of Bite Block				
Interaction of BB and V				
Main Effect of Masking				
Interaction of M and V				
Interaction of BB and M				
Main Effect of Vowel				
Details of Interactions:				
Main Effect of Bite Block				
Interaction of BB and V				
Main Effect of Masking				
Interaction of M and V				
Interaction of BB and M				
Main Effect of Vowel	★/★★(all)			
Details of Interactions:				
heat	least variability			
hit	more variability			
hat	greatest variability			

★★=p<.01, ★=p<.05

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Fig. 7.21. Overview of Changes in F2 and F1 in /i/ for Each Adult with Normal Hearing



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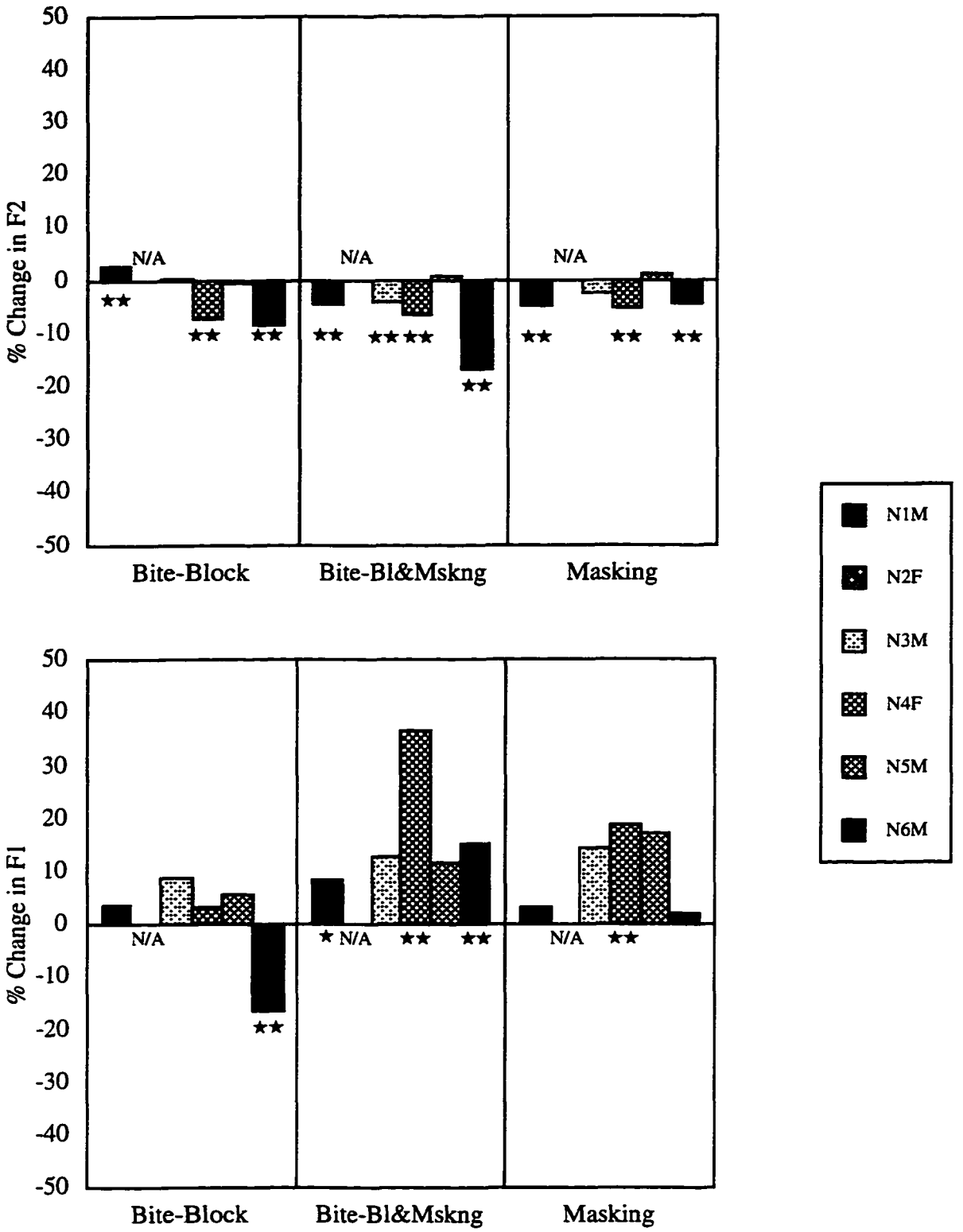


Fig. 7.22. Overview of Changes in F2 and F1 in /I/ for Each Adult with Normal Hearing

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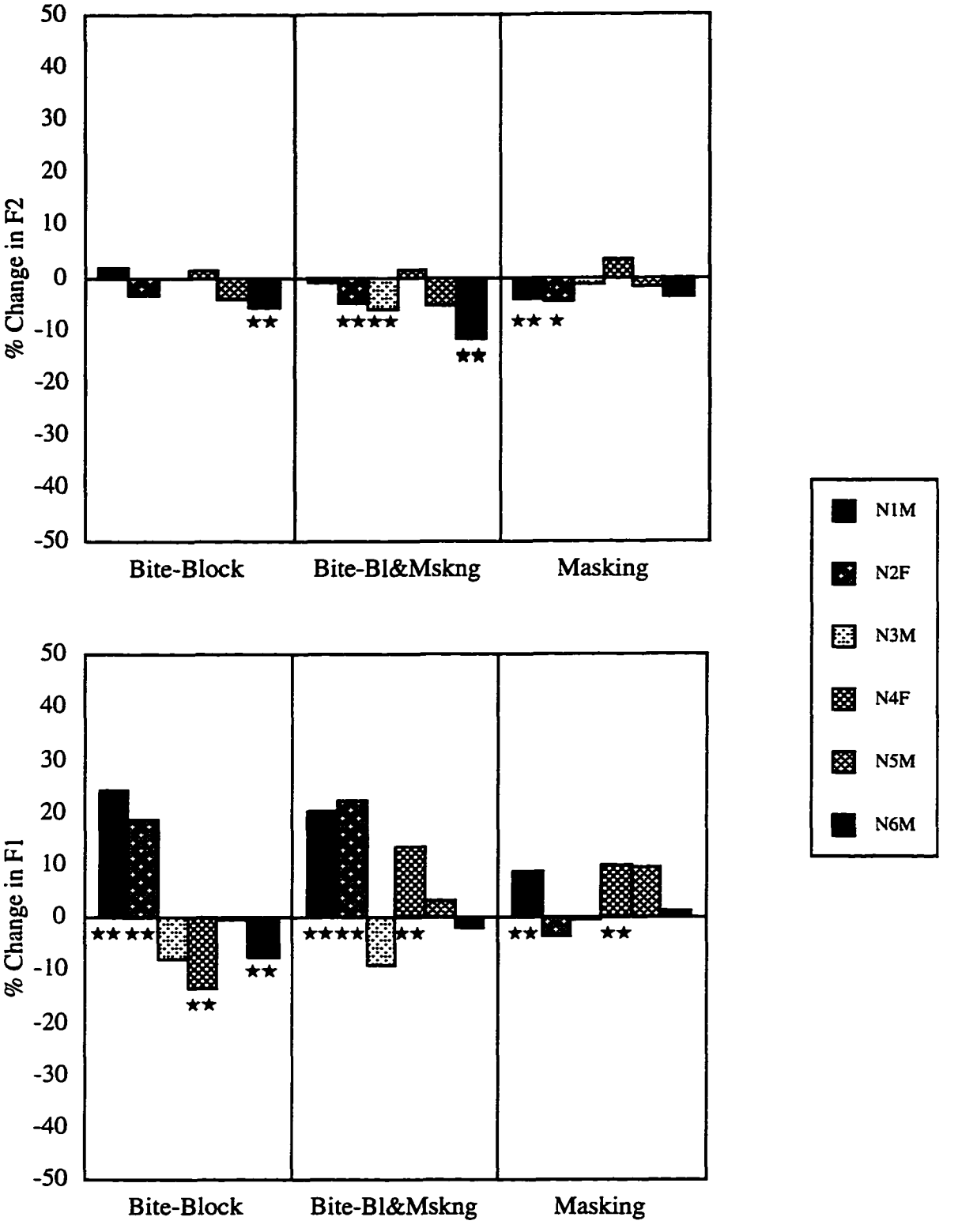


Fig. 7.23. Overview of Changes in F2 and F1 in /ae/ for Each Adult with Normal Hearing

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Summary of Results from the Adults with Normal Hearing

Bite-Block Effects

Tables 7.4 and 7.26 illustrate the overall summary statements made here. The bite-block lowered F2, as predicted by computer simulation. It significantly lowered heat F2 in the group, and yielded a significant main effect of bite block across all vowels for every individual subject. A bite-block-by-vowel interaction was shown for a majority of individual subjects, but no overall pattern was revealed. Individuals varied with regard to which vowels were most affected by bite-block effects on F2.

Overall, bite-block conditions raised F1, as predicted by computer simulation for a greater-than-normal interincisor distance. A raised F1 was seen in the group for all vowels. In the individual speakers, F1 was raised in /i/ and /I/, but most often lowered for /ae/. Computer simulation also predicted that F1 would be lowered for a less-than-normal interincisor distance. A significant effect of bite block on F1 was not seen for the group, but was revealed in a majority of individual speakers. A bite-block-by-vowel interaction achieved significance for every individual talker: heat and hit showed little effect, but hat F1 exhibited significant differences between bite-block and non-bite-block conditions.

Masking Effects

Tables 7.5 and 7.27 illustrate the overall summary statements made here. Masking conditions lowered F2, the same direction of change as seen in bite-block conditions. A significant effect of masking was seen for /i/ F2 in the group and a main effect of masking was shown across vowels by a majority of the individual subjects. A masking-by-vowel interaction was exhibited by a majority of the individual talkers. No overall pattern across individuals was displayed, but results indicated that two subjects were particularly affected by masking conditions on F2 in all vowels.

Masking conditions raised F1, the same direction of change as seen in bite-block conditions for /i/ and /I/. (Analysis by individual had shown a lowered F1 for /ae/,

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although group analysis showed that both bite-block and masking conditions raised F1 overall.) No significant effect of masking was exhibited for any vowel by the group, but all of the individual subjects showed a main effect of masking, collapsed across vowels. A masking-by-vowel interaction reached significance in a majority of the individual speakers. Little effect was seen for hat F1, but /i/ and /I/ showed significant differences in F1 between masking and non-masking conditions.

Bite-Block-plus-Masking Effects

Tables 7.6 and 7.28 illustrate the overall summary statements made here. The combination of bite block and masking lowered F2. The condition significantly lowered F2 for /i/ and /ae/ in the group. Both the group results and the individual profiles showed that heat F2 was affected more by bite-block-plus-masking than either bite block or masking alone. Individual profiles revealed that hat F2 was also affected more by bite-block-plus-masking than either of the other test conditions alone.

The bite-block-plus-masking condition raised F1. For the group the effect was significant for hit. Individual profiles showed that across all vowels, masking and bite-block-plus-masking were more detrimental to F1 than bite block alone, however, for hat bite-block and bite-block-plus-masking conditions were more detrimental than masking alone.

Variability

Tables 7.7 - 7.9 and 7.29 illustrate the overall summary statements made here. F2 variability was increased in the bite-block condition for /ae/ for the group, different from the masking or bite-block-plus-masking conditions. No pattern of increased variability was shown to be significant for any one individual talker. F1 variability was not significantly affected.

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A significant main effect of vowel on F1 standard deviation was found for all individuals: hat exhibited greatest F1 variability, hit less, and heat least.

Discussion of and Conclusions Drawn from These Results

It may be concluded from these results that articulatory compensation for a bite block by adults with normal hearing is substantial and immediate, but not perfect, yielding small changes. The practical implications of these changes were not tested. It is not certain that the changes measured acoustically would affect vowel category assignment by listeners.

It may also be concluded that auditory feedback plays some role in articulatory compensation, perhaps especially for tongue placement affecting F2. Even in the masking condition alone formant changes in the same direction as those seen in the bite-block condition were evident, suggesting that both the bite block and masking had a neutralizing effect on vowel production.

Because changes in formant values in test conditions were not as large as computer simulation predicted, the theoretical implication is that substantial, immediate compensation (especially for tongue height) is accomplished peripherally, but it is neither complete nor perfect. While the effects of masking combined with the bite block were not simply additive, performance was diminished when auditory feedback was removed (even in the masking-alone condition), suggesting that model referencing may also play a role in compensation and in on-line monitoring of production. Therefore, the hypothesis that adults with normal hearing compensate completely for a bite block is rejected, but the related hypothesis that auditory feedback plays a role in this compensation is accepted.

Given these findings it was anticipated that the four-year-old children, whose data will be presented next, would exhibit less ability than do adults to compensate for a bite block and greater dependence upon auditory feedback in both normal and perturbed production. It will be seen that the first expectation was supported, but the second was not.

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CHAPTER EIGHT

RESULTS: CHILDREN WITH NORMAL HEARING

The application of this experiment to a group of six children with normal hearing tested the second hypothesis of this dissertation: Four-year-old children with normal hearing perform adult-like compensation for a bite block and auditory feedback plays a role in this compensation.

Acoustic Analysis of Vowels Produced in Four Conditions: Measures of Articulatory Compensation

Group Data

Results were first examined using data averaged across the group of six subjects. The formant frequency values used for statistical tests were recorded in Table 8.1a-c which follows (N/A indicates missing data). For figure presentations, percent change in formant frequency from normal to test conditions was used to illustrate changes in each of the second and first formants.

Direction of Change

The second formant measurements were averaged across the children and examined for overall differences among conditions. The bar graphs on the left side of Figure 8.1 revealed that, like the adults, the children exhibited changes in F2 in test conditions compared to the normal condition. As predicted by computer simulation, both test conditions employing a bite block (B and B+M) resulted in a lowering of F2 from the normal condition. Unlike the adults, who also showed a lowered mean F2 in the masking

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Table 8.1a.--Group Means, % Change, and Standard Deviations of F2 and F1 of "Heat" for the Children with Normal Hearing

Sub-ject	Sex	Condition	Vowel	Mean F2	%Ch in F2	Mean F1	%Ch in F1	F2 SD	F1 SD
C1F	Female	Normal	heat	3474.64	***	480.82	***	130.78	59.98
C2M	Male	Normal	heat	3378.50	***	325.88	***	74.33	16.35
C3F	Female	Normal	heat	3405.89	***	443.00	***	268.34	42.52
C4M	Male	Normal	heat	3429.00	***	460.43	***	172.22	70.08
C5M	Male	Normal	heat	3530.00	***	441.00	***	151.00	75.80
C6F	Female	Normal	heat	3445.33	***	436.33	***	221.45	21.78
Group Means Per Condition				3443.89	***	431.24	***	169.69	47.75
C1F	Female	Bite-Block	heat	2825.50	-18.68	463.13	-3.68	379.08	82.16
C2M	Male	Bite-Block	heat	3007.00	-11.00	376.00	15.38	182.00	43.25
C3F	Female	Bite-Block	heat	3144.44	-7.68	487.33	10.01	383.91	68.63
C4M	Male	Bite-Block	heat	3367.20	-1.80	451.90	-1.85	103.00	69.90
C5M	Male	Bite-Block	heat	3164.00	-10.37	453.00	2.72	174.00	64.20
C6F	Female	Bite-Block	heat	3058.88	-11.22	488.25	11.90	322.01	62.20
Group Means Per Condition				3094.50	-10.13	453.27	5.75	257.33	65.06
C1F	Female	Bite-Bl&Msknq	heat	3006.22	-13.48	471.67	-1.90	259.97	39.69
C2M	Male	Bite-Bl&Msknq	heat	3150.00	-6.76	465.00	42.69	185.34	43.70
C3F	Female	Bite-Bl&Msknq	heat	3272.80	-3.91	468.70	5.80	253.46	65.59
C4M	Male	Bite-Bl&Msknq	heat	3344.25	-2.47	445.00	-3.35	112.61	75.67
C5M	Male	Bite-Bl&Msknq	heat	3043.00	-13.80	491.00	11.34	349.00	25.40
C6F	Female	Bite-Bl&Msknq	heat	2971.46	-13.75	562.39	28.89	289.73	79.99
Group Means Per Condition				3131.29	-9.03	483.96	13.91	241.69	55.01
C1F	Female	Masking	heat	N/A	N/A	N/A	N/A	N/A	N/A
C2M	Male	Masking	heat	3318.00	-1.79	416.00	27.66	119.87	41.59
C3F	Female	Masking	heat	3243.25	-4.78	507.50	14.56	270.90	62.49
C4M	Male	Masking	heat	3508.87	2.33	420.27	-8.72	95.94	60.66
C5M	Male	Masking	heat	3574.00	1.25	471.00	6.80	144.00	36.00
C6F	Female	Masking	heat	3410.55	-1.01	477.27	9.38	269.49	84.15
Group Means Per Condition				3410.93	-0.80	458.41	9.94	180.04	56.98

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Table 8.1b.--Group Means, % Change, and Standard Deviations of F2 and F1 of "Hit" for the Children with Normal Hearing

Subject	Sex	Condition	Vowel	Mean F2	%Ch in F2	Mean F1	%Ch in F1	F2 SD	F1 SD
C1F	Female	Normal	hit	3033.20	***	585.00	***	133.74	98.04
C2M	Male	Normal	hit	2682.14	***	578.43	***	87.07	63.30
C3F	Female	Normal	hit	2713.53	***	777.07	***	146.53	159.49
C4M	Male	Normal	hit	2847.92	***	559.92	***	170.29	76.68
C5M	Male	Normal	hit	2750.00	***	613.40	***	136.44	59.48
C6F	Female	Normal	hit	2739.71	***	845.21	***	125.13	143.47
Group Means Per Condition				2794.42	***	659.84	***	133.20	100.08
C1F	Female	Bite-Block	hit	2468.63	-18.61	631.25	7.91	409.87	82.54
C2M	Male	Bite-Block	hit	2654.44	-1.03	630.00	8.92	141.68	86.90
C3F	Female	Bite-Block	hit	2608.00	-3.89	861.50	10.87	137.46	135.53
C4M	Male	Bite-Block	hit	2854.27	0.22	534.67	-4.51	175.18	68.35
C5M	Male	Bite-Block	hit	2515.71	-8.52	671.00	9.39	221.60	36.55
C6F	Female	Bite-Block	hit	2564.00	-6.41	808.15	-4.38	187.06	80.38
Group Means Per Condition				2610.84	-6.37	689.43	4.70	212.14	81.71
C1F	Female	Bite-Bl&Msknq	hit	2637.00	-13.06	803.90	37.42	185.34	121.99
C2M	Male	Bite-Bl&Msknq	hit	2733.33	1.91	841.11	45.41	124.99	78.86
C3F	Female	Bite-Bl&Msknq	hit	2589.53	-4.57	845.93	8.86	95.99	114.77
C4M	Male	Bite-Bl&Msknq	hit	2818.31	-1.04	539.69	-3.61	143.14	82.40
C5M	Male	Bite-Bl&Msknq	hit	2595.20	-5.63	696.60	13.56	197.16	185.88
C6F	Female	Bite-Bl&Msknq	hit	2465.44	-10.01	746.44	-11.69	133.04	76.98
Group Means Per Condition				2639.80	-5.40	745.61	14.99	146.61	110.15
C1F	Female	Masking	hit	3053.31	0.66	778.46	33.07	117.23	106.38
C2M	Male	Masking	hit	2845.38	6.09	773.25	33.68	105.38	40.99
C3F	Female	Masking	hit	2748.67	1.29	964.25	24.09	147.22	136.94
C4M	Male	Masking	hit	2843.62	-0.15	580.92	3.75	110.53	70.79
C5M	Male	Masking	hit	2859.36	3.98	619.93	1.06	112.58	78.69
C6F	Female	Masking	hit	2701.29	-1.40	779.71	-7.75	290.10	186.97
Group Means Per Condition				2841.94	1.75	749.42	14.65	147.17	103.46

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Table 8.1c.--Group Means, % Change, and Standard Deviations of F2 and F1 of "Hat" for the Children with Normal Hearing

Subject	Sex	Condition	Vowel	Mean F2	%Ch in F2	Mean F1	%Ch in F1	F2 SD	F1 SD
C1F	Female	Normal	hat	2605.47	***	1327.87	***	82.69	78.28
C2M	Male	Normal	hat	2420.00	***	999.40	***	91.78	126.08
C3F	Female	Normal	hat	2574.62	***	1356.54	***	186.48	187.95
C4M	Male	Normal	hat	2443.20	***	1396.60	***	119.07	76.48
C5M	Male	Normal	hat	2552.46	***	1329.38	***	138.05	105.48
C6F	Female	Normal	hat	2562.94	***	1338.56	***	61.47	69.94
Group Means Per Condition				2526.45	***	1291.39	***	113.26	107.37
C1F	Female	Bite-Block	hat	1967.75	-24.48	791.00	-40.43	285.95	132.02
C2M	Male	Bite-Block	hat	2394.11	-1.07	882.89	-11.66	106.98	100.14
C3F	Female	Bite-Block	hat	2383.08	-7.44	1011.00	-25.47	144.55	156.38
C4M	Male	Bite-Block	hat	2268.00	-7.17	1356.75	-2.85	95.78	143.75
C5M	Male	Bite-Block	hat	2508.10	-1.74	1038.80	-21.86	152.23	148.02
C6F	Female	Bite-Block	hat	2283.19	-10.92	1171.88	-12.45	172.57	108.70
Group Means Per Condition				2300.71	-8.80	1042.05	-19.12	159.68	131.50
C1F	Female	Bite-Bl&Mskng	hat	2243.79	-13.88	1110.29	-16.39	201.09	84.03
C2M	Male	Bite-Bl&Mskng	hat	2432.64	0.52	1087.73	8.84	132.88	92.48
C3F	Female	Bite-Bl&Mskng	hat	2392.69	-7.07	1202.06	-11.39	115.67	194.42
C4M	Male	Bite-Bl&Mskng	hat	N/A	N/A	N/A	N/A	N/A	N/A
C5M	Male	Bite-Bl&Mskng	hat	2467.22	-3.34	1104.56	-16.91	211.07	281.21
C6F	Female	Bite-Bl&Mskng	hat	2331.10	-9.05	997.20	-25.50	141.59	146.08
Group Means Per Condition				2373.49	-6.56	1100.37	-12.27	160.46	159.64
C1F	Female	Masking	hat	2476.33	-4.96	1332.56	0.35	45.18	101.80
C2M	Male	Masking	hat	2440.36	0.84	1252.93	25.37	78.84	84.51
C3F	Female	Masking	hat	2589.81	0.59	1347.06	-0.70	82.41	132.36
C4M	Male	Masking	hat	2388.25	-2.26	1305.75	-6.56	160.00	87.47
C5M	Male	Masking	hat	2474.27	-3.06	1552.13	16.76	65.06	126.19
C6F	Female	Masking	hat	2579.18	0.63	1230.18	-8.10	112.70	101.44
Group Means Per Condition				2491.37	-1.37	1336.77	4.52	90.70	105.63

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condition (M), the children showed minimal lowering of F2 in /i/ and /ae/ and a raising of F2 in /I/.

First formant measurements were next examined. The bar graphs on the right side of Figure 8.1 revealed that, as was true for the adults, there were larger changes in F1 than in F2. As predicted by computer simulation, both test conditions employing a bite block (B and B+M) resulted in a raising of F1 from the normal condition for heat and hit, but unlike the group of adults, F1 in hat was lowered. It will be remembered from "Chapter Four: Computer Simulation of Bite-Block Effects on Formant Frequencies" that computer simulation predicted that formant values for the open vowel /ae/ may be either raised or lowered in a bite-block condition, depending on whether the bite block creates a greater-than or less-than-normal interincisor distance. It may be that the smaller, 10-mm bite block used with the children resulted in a less-than-normal interincisor distance. The masking condition (M) produced changes in F1 in the same direction as bite-block conditions for heat and hit, as it had for the adults.

Magnitude of Change

The graphs on the left side of Figure 8.1 revealed that the bite-block and bite-block-plus-masking conditions produced moderate changes in F2 and the masking condition produced negligible changes, in a pattern that was reasonably similar for the three vowels. The magnitude of the lowering of F2 in the bite-block and the bite-block-plus-masking conditions was roughly similar (11% or less), while changes in the masking condition were much smaller (2% or less). To determine whether any of the observed differences were statistically significant, a repeated measures one-way analysis of variance by condition was performed separately for each vowel because Subjects C1F and C4M had missing data for /i/ and /ae/, respectively. (See Tables 8.1a and 8.1c.) The results of the repeated measures ANOVA for F2 are reported in Table 8.2a for each vowel. A main effect of condition was found for every vowel, with significance values greater for the close vowels /i/ (p=.0014) and /I/ (p=.0053) than for the open vowel /ae/ (p=.0221). Post hoc LSD tests of paired

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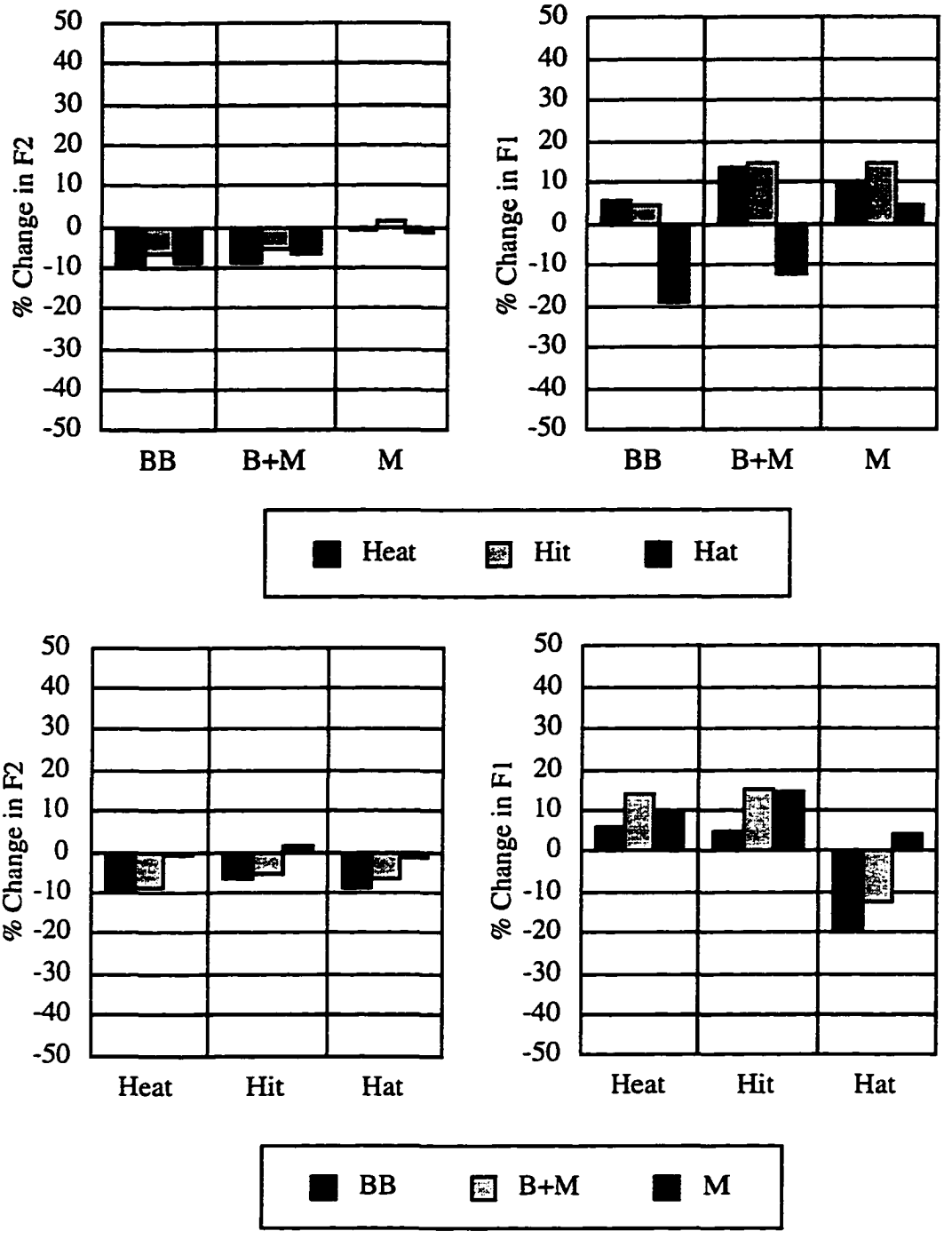


Fig. 8.1. Mean % Change from Normal Condition in F2 and F1 in Bite-Block (BB), Bite-Block-Plus-Masking (B+M), and Masking (M) Conditions for the Children with Normal Hearing

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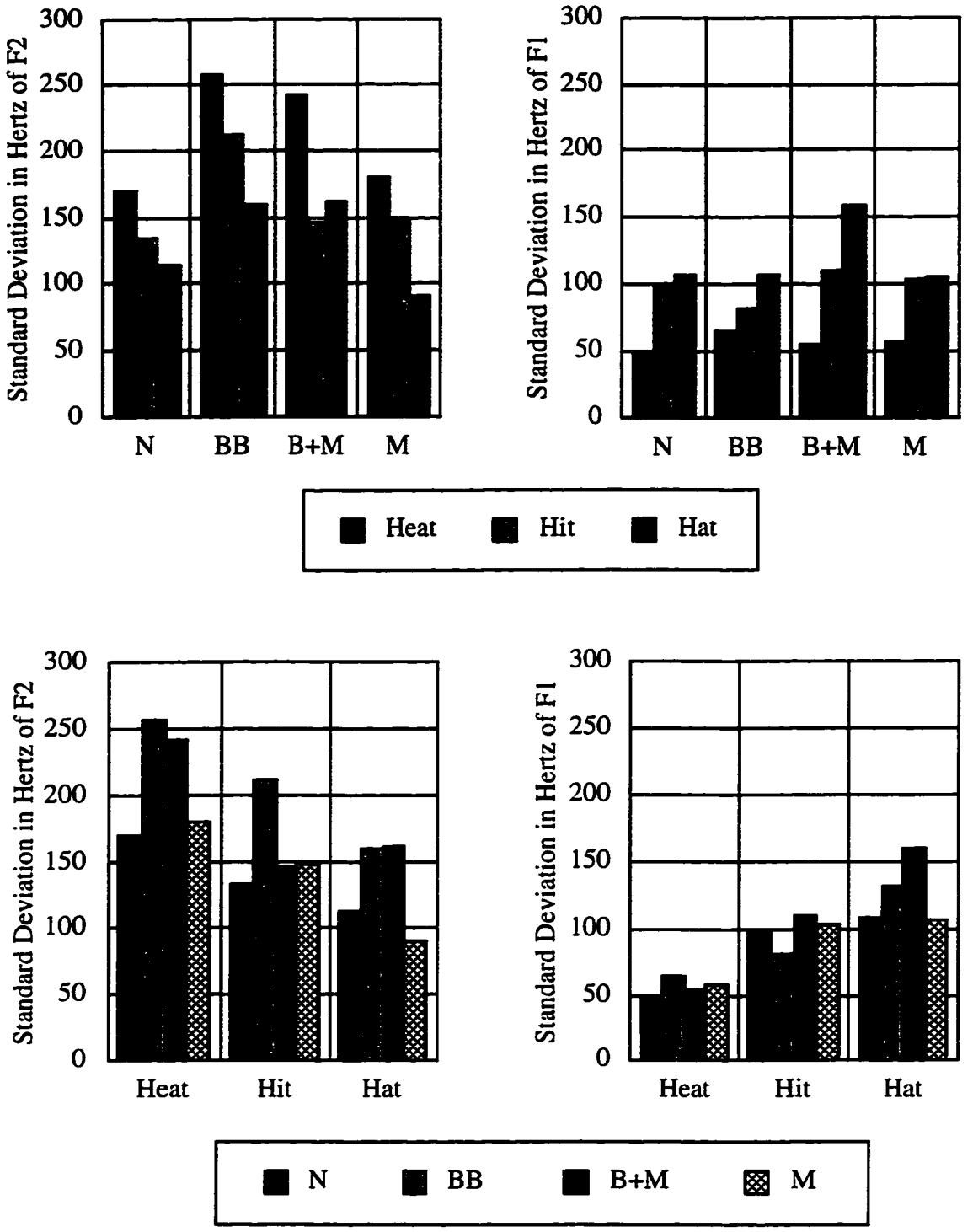


Fig. 8.2. Mean Standard Deviation in Hertz of F2 and F1 in Bite-Block (BB), Bite-Block-Plus-Masking (B+M), and Masking (M) Conditions for the Children with Normal Hearing

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Table 8.2a.--Repeated Measures One-Way Analysis of Variance: Mean F2 for Group of Children with Normal Hearing

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Heat					
Condition	371974.80	3	123991.60	10.04	.0014★★
Error	148268.60	12	12355.70		
Hit					
Condition	232451.20	3	77483.73	6.39	.0053★★
Error	182013.50	15	12134.24		
Hat					
Condition	188565.40	3	62855.14	4.66	.0221★
Error	161851.80	12	13487.65		

Table 8.2b.--Repeated Measures One-Way Analysis of Variance: Mean F1 for Group of Children with Normal Hearing

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Heat					
Condition	10723.01	3	3574.34	3.40	.0536
Error	12621.03	12	1051.75		
Hit					
Condition	34541.37	3	11513.79	2.32	.1172
Error	74594.30	15	4972.95		
Hat					
Condition	406172.70	3	135390.90	9.87	.0015★★
Error	164546.60	12	13712.20		

Table 8.2c.--Repeated Measures One-Way Analysis of Variance: Mean Standard Deviation of F2 for Group of Children with Normal Hearing

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Heat					
Condition	16184.09	3	5394.70	1.60	.2421
Error	40574.00	12	3381.17		
Hit					
Condition	22683.71	3	7561.23	1.79	.1930
Error	63503.70	15	4233.58		
Hat					
Condition	29381.46	3	9793.82	3.66	.0442★
Error	32143.68	12	2678.64		

★★ = $p<.01$, ★ = $p<.05$

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Table 8.2d.--Repeated Measures One-Way Analysis of Variance: Mean Standard Deviation of F1 for Group of Children with Normal Hearing

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Heat					
Condition	751.79	3	250.60	.68	.5800
Error	4410.46	12	367.54		
Hit					
Condition	2665.25	3	888.42	.60	.6221
Error	22044.23	15	1469.61		
Hat					
Condition	7812.47	3	2604.15	1.63	.2348
Error	19189.64	12	1599.14		

★★ = p<.01, ★ = p<.05

comparisons between the F2 means of each condition showed that the bite-block and the bite-block-plus-masking conditions lowered F2 of every vowel significantly. (See Tables 8.3 a, b, and c.) Because the masking condition had so little effect, F2 values of each vowel in the masking condition also differed significantly from F2 values in the bite-block and the bite-block-plus-masking conditions in all comparisons except the masking versus bite-block-plus-masking test for /ae/. Conversely, the observation that the effects of bite-block and bite-block-plus-masking conditions were similar was supported by a failure to find a significant difference between the bite-block and the bite-block-plus-masking conditions in every vowel.

The graphs on the right side of Figure 8.1 showed that test conditions produced larger changes in F1 than in F2, some as large as roughly 20%. For /i/ and /ɪ/, the bite block alone had a modest effect, but masking alone had a larger effect and the bite block had an additional effect when masking was present. However, the data for /ae/ looked quite different. The bite block alone had a large effect, but less an effect when masking was present. A significant effect of condition on F1 was found only for /ae/ (p=.0015).

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Table 8.3a.--Summary of Results of Post Hoc Tests of the Main Effect of Condition on Heat F2 for Children with Normal Hearing

Mean /i/ F2 in Four Conditions:			
N = 3437.74	BB = 3148.30	B+M = 3156.30	M = 3410.93
	N v. BB	p = .00143★★	
	N v. B+M	p = .00175★★	
	N v. M	p = .70960	
	BB v. B+M	p = .91130	
	BB v. M	p = .00284★★	
	B+M v. M	p = .00350★★	

Table 8.3b.--Summary of Results of Post Hoc Tests of the Main Effect of Condition on Hit F2 for Children with Normal Hearing

Mean /I/ F2 in Four Conditions:			
N = 2794.42	BB = 2610.84	B+M = 2639.80	M = 2841.94
	N v. BB	p = .01130★	
	N v. B+M	p = .02806★	
	N v. M	p = .46649	
	BB v. B+M	p = .65537	
	BB v. M	p = .00245★★	
	B+M v. M	p = .00623★★	

Table 8.3c.--Summary of Results of Post Hoc Tests of the Main Effect of Condition on Hat F2 for Children with Normal Hearing

Mean /ae/ F2 in Four Conditions:			
N = 2543.10	BB = 2307.25	B+M = 2373.49	M = 2511.99
	N v. BB	p = .00748★★	
	N v. B+M	p = .03954★	
	N v. M	p = .67941	
	BB v. B+M	p = .38488	
	BB v. M	p = .01642★	
	B+M v. M	p = .08378	

Table 8.3d.--Summary of Results of Post Hoc Tests of the Main Effect of Condition on Hat F1 for Children with Normal Hearing

Mean /ae/ F1 in Four Conditions:			
N = 1270.35	BB = 979.11	B+M = 1100.37	M = 1342.97
	N v. BB	p = .00199★★	
	N v. B+M	p = .04055★	
	N v. M	p = .34616	
	BB v. B+M	p = .12752	
	BB v. M	p = .00036★★	
	B+M v. M	p = .00663★★	

★★ = p<.01, ★ = p<.05

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Table 8.3e.--Summary of Results of Post Hoc Tests of the Main Effect of Condition on Hat F2SD for Children with Normal Hearing

Mean /ae/ F2SD in Four Conditions:			
N = 112.09	BB = 172.46	B+M = 160.46	M = 76.84
	N v. BB	p = .08999	
	N v. B+M	p = .16528	
	N v. M	p = .30262	
	BB v. B+M	p = .72039	
	BB v. M	p = .01281★	
	B+M v. M	p = .02525★	

★★ = p<.01, ★ = p<.05

Post hoc LSD tests (See Table 8.3d.) supported what Figure 8.1 revealed, that the bite block significantly lowered /ae/ F1 (p=.00199), as did the combination of bite-block-plus-masking (p=.04055), quite different from the masking condition, which had almost no effect (BB v. M, p=.00036); B+M v. M, p=.00663).

The mean standard deviations in Hertz of F2 and F1 were next examined (Figure 8.2) to determine if there were overall differences among conditions in terms of variability of production. (See Tables 8.2c and 8.2d.) No significant main effect of condition was shown for F1 standard deviation, but /ae/ F2 standard deviation exhibitied a main effect of condition. (See Table 8.2c.) Post hoc LSD tests of this main effect indicated that the bite-block and bite-block-plus-masking conditions increased F2 variability while the masking condition decreased it (BB v. M, p=.01281; B+M v. M, p=.02525).

Summary

Tables 8.4 - 8.9 summarize the effects of all independent variables on all dependent variables for the group of children and facilitate comparisons to the previous findings for the group of adults with normal hearing. The reader is reminded that information from post hoc tests is provided only where a significant main effect of condition was obtained for a dependent variable.

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The data from the group of children with normal hearing revealed that:

A. the bite block lowered F2, as predicted by computer simulation and as seen in the group of adults. The changes were larger for the children; F2 in every vowel was lowered significantly. For the adults, only /i/ F2 had been lowered significantly. The bite block raised F1 for /i/ and /I/, as predicted by computer simulation for a greater-than-normal interincisor distance, and as seen in the adults. Hat F1 was lowered, as predicted by computer simulation for a less-than-normal interincisor distance. The significant lowering may have resulted from the use of a 10-mm bite block with the children. The adults were given 20-mm bite blocks and no significant effects on F1 were shown. (See Table 8.4.)

B. the masking condition had very little effect on F2, quite different from the bite block. /i/ F2 had been lowered significantly in the adults. The masking condition resulted in changes in F1 for /i/ and /I/ that were in the same direction as the bite block, but in the opposite direction for /ae/. (See Table 8.5.)

C. the bite-block-plus-masking condition also changed F2 and F1 in the same directions as the bite block alone. F2 was significantly lowered in every vowel, in contrast to the small effect of masking. F1 in /ae/ was significantly lowered, as it was in the bite-block condition, opposite in direction to the effect of masking. (See Table 8.6.)

D. the bite-block and bite-block-plus-masking conditions increased /ae/ F2 variability, but not significantly, as with the adults. Masking decreased /ae/ F2 variability, though not significantly. (See Tables 8.7 - 8.9.)

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Table 8.4.--Summary of Bite-Block Effects on F2 and F1 for Groups of Subjects

	Adults with Normal Hearing	**Children with Normal Hearing**	Adults with Profound Hearing Loss	Adults with Severe Hearing Loss
F2 Direction of Change:				
heat	lowered	lowered		
hit	lowered	lowered		
hat	lowered	lowered		
% Change	<3%	<11%		
Post Hoc Tests of Main Effect of Condition for Heat:				
N v. BB	↓ ★	↓ ★★		
Hit:				
N v. BB		↓ ★		
Hat:				
N v. BB		↓ ★★		
F1 Direction of Change:				
heat	raised	raised		
hit	raised	raised		
hat	raised	lowered		
% Change	<8%	<20%		
Post Hoc Tests of Main Effect of Condition for Heat:				
N v. BB				
Hit:				
N v. BB				
Hat:				
N v. BB		↓ ★★		

★★=p<.01, ★=p<.05, ↑ = raised formant, ↓ = lowered formant

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Table 8.5.--Summary of Masking Effects on F2 and F1 for Groups of Subjects

	Adults with Normal Hearing	**Children with Normal Hearing**	Adults with Profound Hearing Loss	Adults with Severe Hearing Loss
F2 Direction of Change:				
heat	lowered	lowered		
hit	lowered	raised		
hat	lowered	lowered		
% Change	<4%	<2%		
Post Hoc Tests of Main Effect of Condition for Heat:				
N v. M	↓ ★			
BB v. M		★★		
Hit:				
N v. M				
BB v. M		★★		
Hat:				
N v. M				
BB v. M		★		
F1 Direction of Change:				
heat	raised	raised		
hit	raised	raised		
hat	raised	raised		
% Change	<12%	<15%		
Post Hoc Tests of Main Effect of Condition for Heat:				
N v. M				
BB v. M				
Hit:				
N v. M				
BB v. M				
Hat:				
N v. M				
BB v. M		★★		

★★=p<.01, ★=p<.05, ↑ = raised formant, ↓ = lowered formant

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Table 8.6.--Summary of Bite-Block-Plus-Masking Effects on F2 and F1 for Groups of Subjects

	Adults with Normal Hearing	**Children with Normal Hearing**	Adults with Profound Hearing Loss	Adults with Severe Hearing Loss
F2 Direction of Change:				
heat	lowered	lowered		
hit	lowered	lowered		
hat	lowered	lowered		
% Change	<7%	<10%		
Post Hoc Tests of Main Effect of Condition for Heat:				
N v. BM	↓ ★★	↓ ★★		
BB v. B+M	★★			
M v. B+M	★★	★★		
Hit:				
N v. BM		↓ ★		
BB v. B+M				
M v. B+M		★★		
Hat:				
N v. BM	↓ ★★	↓ ★		
BB v. B+M				
M v. B+M				
F1 Direction of Change:				
heat	raised	raised		
hit	raised	raised		
hat	raised	lowered		
% Change	<17%	<15%		
Post Hoc Tests of Main Effect of Condition for Heat:				
N v. BM				
BB v. B+M				
M v. B+M				
Hit:				
N v. BM	↑ ★★			
BB v. B+M	★★			
M v. B+M				
Hat:				
N v. BM		↓ ★		
BB v. B+M				
M v. B+M		★★		

★★=p<.01, ★=p<.05, ↑ = raised formant, ↓ = lowered formant

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Table 8.7.--Summary of Bite-Block Effects on F2SD and F1SD for Groups of Subjects

	Adults with Normal Hearing	**Children with Normal Hearing**	Adults with Profound Hearing Loss	Adults with Severe Hearing Loss
Post Hoc Tests of Main Effect of Condition for Heat F2SD: N v. BB				
Hit F2SD: N v. BB				
Hat F2SD: N v. BB	↑ ★★			
Post Hoc Tests of Main Effect of Condition for Heat F1SD: N v. BB				
Hit F1SD: N v. BB				
Hat F1SD: N v. BB				

★★=p<.01, ★=p<.05, ↑ = increased variability, ↓ = decreased variability

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Table 8.8.--Summary of Masking Effects on F2SD and F1SD for Groups of Subjects

	Adults with Normal Hearing	**Children with Normal Hearing**	Adults with Profound Hearing Loss	Adults with Severe Hearing Loss
Post Hoc Tests of Main Effect of Condition for Heat F2SD:				
N v. M				
BB v. M				
Hit F2SD:				
N v. M				
BB v. M				
Hat F2SD:				
N v. M				
BB v. M	★	★		
Post Hoc Tests of Main Effect of Condition for Heat F1SD:				
N v. M				
BB v. M				
Hit F1SD:				
N v. M				
BB v. M				
Hat F1SD:				
N v. M				
BB v. M				

★★=p<.01, ★=p<.05, ↑ = increased variability, ↓ = decreased variability

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Table 8.9.--Summary of Bite-Block-Plus-Masking Effects on F2SD and F1SD for Groups of Subjects

	Adults with Normal Hearing	**Children with Normal Hearing**	Adults with Profound Hearing Loss	Adults with Severe Hearing Loss
Post Hoc Tests of Main Effect of Condition for Heat F2SD:				
N v. B+M				
BB v. B+M				
M v. B+M				
Hit F2SD:				
N v. B+M				
BB v. B+M				
M v. B+M				
Hat F2SD:				
N v. B+M				
BB v. B+M	★★			
M v. B+M		★		
Post Hoc Tests of Main Effect of Condition for Heat F1SD:				
N v. B+M				
BB v. B+M				
M v. B+M				
Hit F1SD:				
N v. B+M				
BB v. B+M				
M v. B+M				
Hat F1SD:				
N v. B+M				
BB v. B+M				
M v. B+M				

★★=p<.01, ★=p<.05, ↑ = increased variability, ↓ = decreased variability

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Individual Data

To discover the distinctive patterns of compensatory adjustments made by individuals in response to test conditions, the data from each child were analyzed separately. (See Tables 8.10 - 8.15 and Figures 8.3 - 8.8.)

Direction of Change

F2

Overall, conditions employing a bite block (B and B+M) lowered F2 from the normal condition. Four of the six children exhibited this pattern of change. The pattern was consistent with predictions from computer simulation. The only exceptions were a slight raising of F2 in /I/ and /ae/ in the bite-block-plus-masking condition for C2M (Figure 8.4) and in /I/ in the bite-block condition for C4M (Figure 8.6).

The masking condition (M) resulted in changes in both directions for each of the three vowels. F2 in /I/ was raised in four of the six children: C1F, C2M, C3F, and C5M (Figures 8.3 - 8.5 and 8.7). F2 in /i/ was lowered in three of the five children for whom data were available: C2M, C3F, and C6F (Figures 8.4, 8.5 and 8.8). F2 in /ae/ was lowered as many times as it was raised.

F1

Conditions employing a bite block (B and B+M) resulted in a raising of F1 for heat and hit in a majority of the children. This pattern of change was also consistent with predictions from computer simulation for a greater-than-normal interincisal distance. C2M, C3F and C5M (Figures 8.4, 8.5 and 8.7) showed patterns of consistent raising. C1F and C6F (Figures 8.3 and 8.8) showed mixed patterns. The bite-block-plus-masking effect was in contrast to the masking effect for C1F, but followed the masking effect in C6F.

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Conversely, C4M (Figure 8.6) lowered /i/ and /I/ F1 in bite block and bite-block-plus-masking conditions, but the bite-block condition lowered F1 for hat in all the children, and the bite-block-plus-masking condition lowered F1 for hat in four of the five children for whom data were available. C2M (Figure 8.4) was the exception, with the bite-block-plus-masking effect following the masking effect in raising /ae/ F1. Computer simulation predicted a lowering of F1 for a less-than-normal interincisal distance, perhaps a consequence of the 10-mm bite block used by this group.

Masking alone (M) raised F1 for heat in four of five of the children for whom data were available (C4M was the exception - Figure 8.6) and for hit in five of six of the children (C6F was the exception - Figure 8.8). Masking resulted in changes in both directions for hat: /ae/ F1 was raised in half the children and lowered in the other half.

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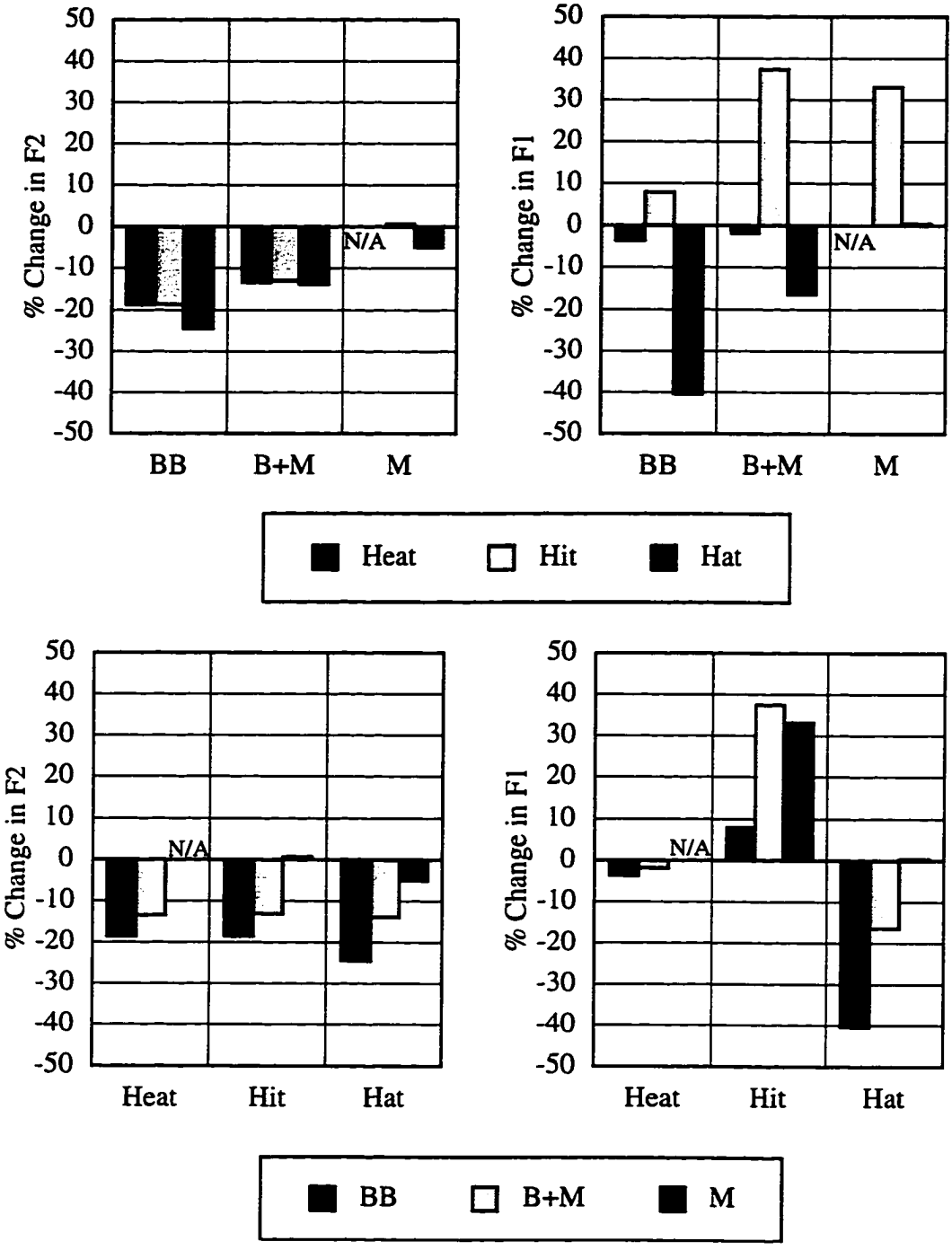
Table 8.10.--Subject C1F: Means, Standard Deviations and Percent Change in Formants from Normal Condition to Test Conditions

Vowel	Condition	N	Mean F2	% Ch F2	Mean F1	% Ch F1	F2 St Dev	F1 St Dev
Heat	Normal	11	3474.64	***	480.82	***	130.78	59.98
	Bite Block	8	2825.50	-18.68	463.13	-3.68	379.08	82.16
	Bite Block and Masking	9	3006.22	-13.48	471.67	-1.90	259.97	39.69
	Masking	1	N/A[1]	N/A	N/A	N/A	N/A	N/A
Hit	Normal	10	3033.20	***	585.00	***	133.74	98.04
	Bite Block	8	2468.63	-18.61	631.25	7.91	409.87	82.54
	Bite Block and Masking	10	2637.00	-13.06	803.90	37.42	185.34	121.99
	Masking	13	3053.31	0.66	778.46	33.07	117.23	106.38
Hat	Normal	15	2605.47	***	1327.87	***	82.69	78.28
	Bite Block	16	1967.75	-24.48	791.00	-40.43	285.95	132.02
	Bite Block and Masking	14	2243.79	-13.88	1110.29	-16.39	201.09	84.03
	Masking	9	2476.33	-4.96	1332.56	0.35	45.18	101.80

[1]All but one token in the Masking Condition for heat were rejected because the F1 measures were very poorly resolved. F0 was completely dominant in the F1 region. Criterion for inclusion of a condition was a minimum of eight tokens in which both F1 and F2 measures were obtained.

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Fig. 8.3. % Change from Normal Condition in F2 and F1 in Bite-Block (BB), Bite-Block-Plus-Masking (B+M), and Masking (M) Conditions for Subject C1F



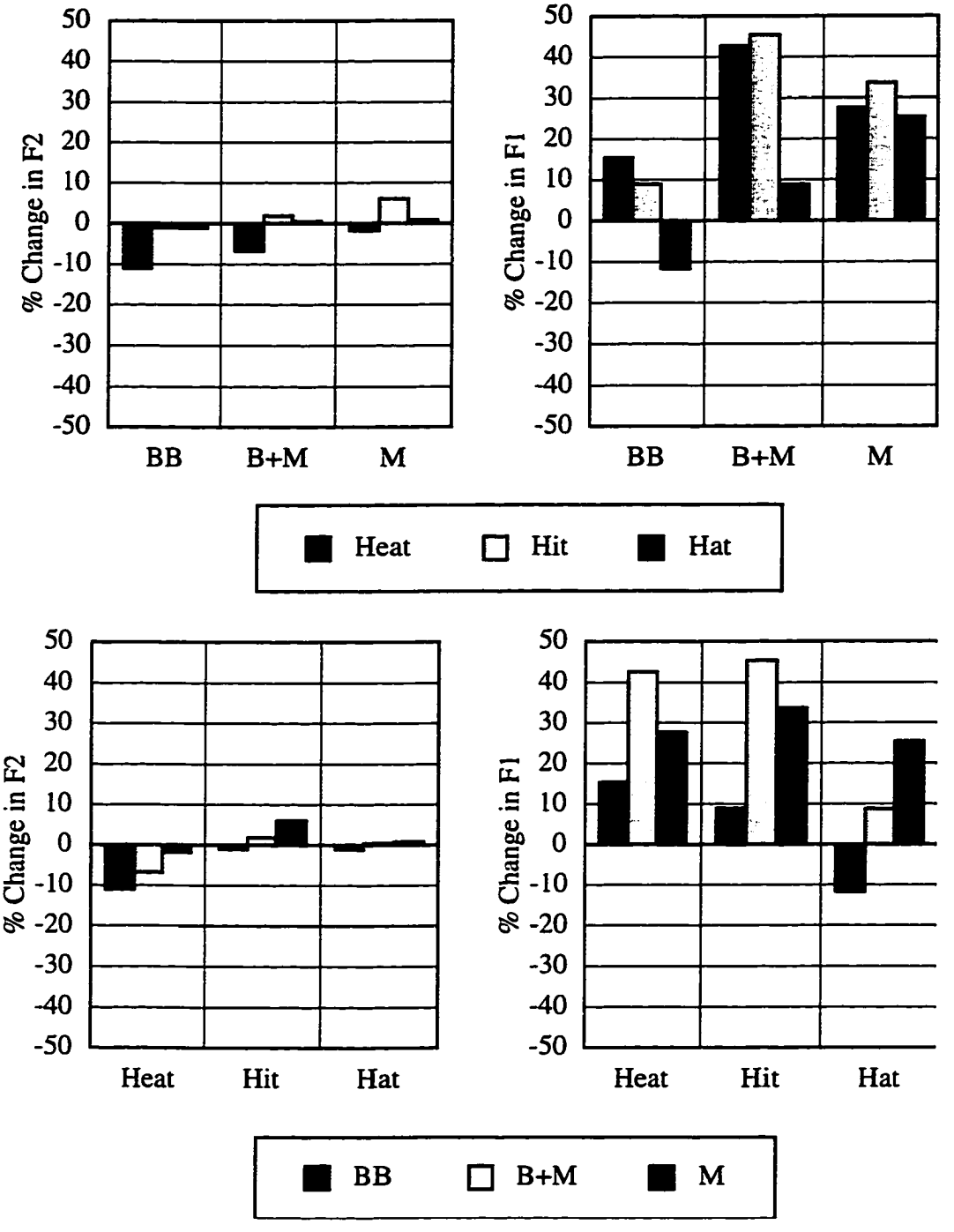
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Table 8.11.--Subject C2M: Means, Standard Deviations and Percent Change in Formants from Normal Condition to Test Conditions

Vowel	Condition	N	Mean F2	% Ch F2	Mean F1	% Ch F1	F2 St Dev	F1 St Dev
Heat	Normal	16	3378.50	***	325.88	***	74.33	16.35
	Bite Block	12	3007.00	-11.00	376.00	15.38	182.00	43.25
	Bite Block and Masking	11	3150.00	-6.76	465.00	42.69	185.34	43.70
	Masking	11	3318.00	-1.79	416.00	27.66	119.87	41.59
Hit	Normal	16	2682.14	***	578.43	***	87.07	63.30
	Bite Block	14	2654.44	-1.03	630.00	8.92	141.68	86.90
	Bite Block and Masking	12	2733.33	1.91	841.11	45.41	124.99	78.86
	Masking	9	2845.38	6.09	773.25	33.68	105.38	40.99
Hat	Normal	16	2420.00	***	999.40	***	91.78	126.08
	Bite Block	13	2394.11	-1.07	882.89	-11.66	106.98	100.14
	Bite Block and Masking	16	2432.64	0.52	1087.73	8.84	132.88	92.48
	Masking	15	2440.36	0.84	1252.93	25.37	78.84	84.51

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Fig. 8.4. % Change from Normal Condition in F2 and F1 in Bite-Block (BB), Bite-Block-Plus-Masking (B+M), and Masking (M) Conditions for Subject C2M



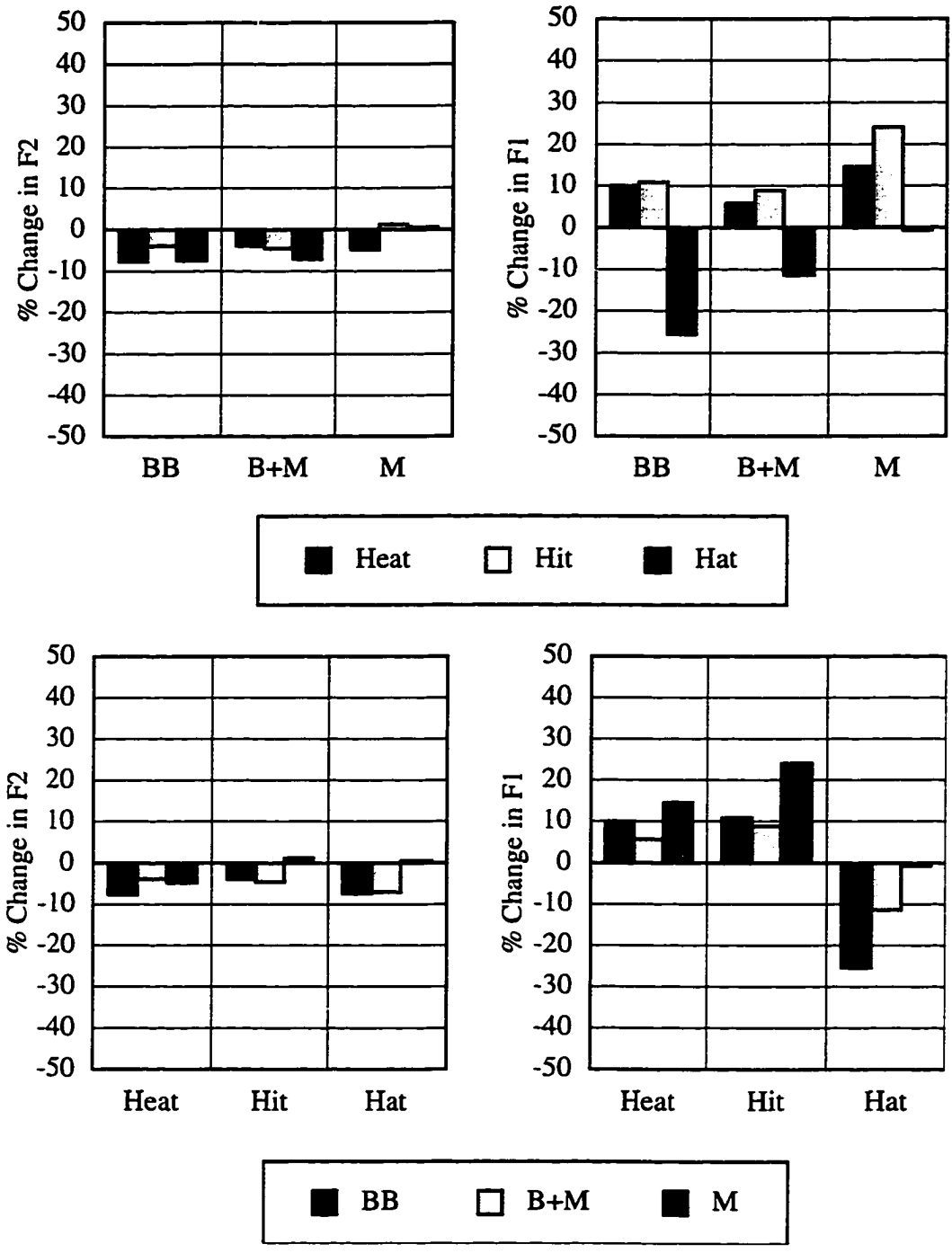
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Table 8.12.--Subject C3F: Means, Standard Deviations and Percent Change in Formants from Normal Condition to Test Conditions

Vowel	Condition	N	Mean F2	% Ch F2	Mean F1	% Ch F1	F2 St Dev	F1 St Dev
Heat	Normal	9	3405.89	***	443.00	***	268.34	42.52
	Bite Block	9	3144.44	-7.68	487.33	10.01	383.91	68.63
	Bite Block and Masking	10	3272.80	-3.91	468.70	5.80	253.46	65.59
	Masking	8	3243.25	-4.78	507.50	14.56	270.90	62.49
Hit	Normal	15	2713.53	***	777.07	***	146.53	159.49
	Bite Block	12	2608.00	-3.89	861.50	10.87	137.46	135.53
	Bite Block and Masking	15	2589.53	-4.57	845.93	8.86	95.99	114.77
	Masking	12	2748.67	1.29	964.25	24.09	147.22	136.94
Hat	Normal	13	2574.62	***	1356.54	***	186.48	187.95
	Bite Block	12	2383.08	-7.44	1011.00	-25.47	144.55	156.38
	Bite Block and Masking	16	2392.69	-7.07	1202.06	-11.39	115.67	194.42
	Masking	16	2589.81	0.59	1347.06	-0.70	82.41	132.36

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Fig. 8.5. % Change from Normal Condition in F2 and F1 in Bite-Block (BB), Bite-Block-Plus-Masking (B+M), and Masking (M) Conditions for Subject C3F



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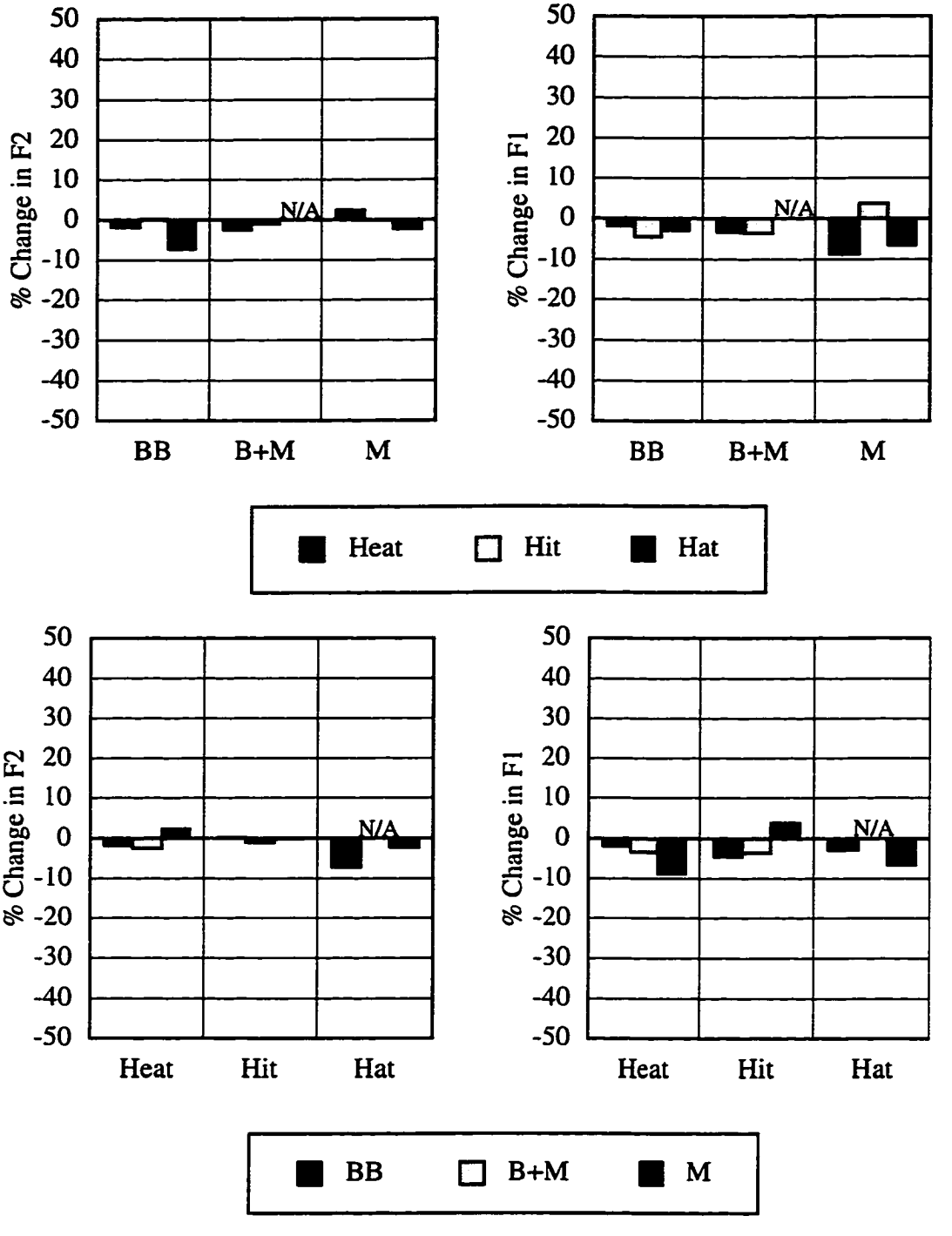
Table 8.13.--Subject C4M: Means, Standard Deviations and Percent Change in Formants from Normal Condition to Test Conditions

Vowel	Condition	N	Mean F2	% Ch F2	Mean F1	% Ch F1	F2 St Dev	F1 St Dev
Heat	Normal	14	3429.00	***	460.43	***	172.22	70.08
	Bite Block	10	3367.20	-1.80	451.90	-1.85	103.00	69.90
	Bite Block and Masking	8	3344.25	-2.47	445.00	-3.35	112.61	75.67
	Masking	15	3508.87	2.33	420.27	-8.72	95.94	60.66
Hit	Normal	13	2847.92	***	559.92	***	170.29	76.68
	Bite Block	15	2854.27	0.22	534.67	-4.51	175.18	68.35
	Bite Block and Masking	13	2818.31	-1.04	539.69	-3.61	143.14	82.40
	Masking	13	2843.62	-0.15	580.92	3.75	110.53	70.79
Hat	Normal	10	2443.20	***	1396.60	***	119.07	76.48
	Bite Block	8	2268.00	-7.17	1356.75	-2.85	95.78	143.75
	Bite Block and Masking	6	N/A[2]	N/A	N/A	N/A	N/A	N/A
	Masking	8	2388.25	-2.25	1305.75	-6.51	160.00	87.47

[2]All but six tokens in the bite-block-plus-masking condition for hat were rejected because both F2 and F1 measures were poorly resolved over very large bandwidths. Criterion for inclusion of a condition was a minimum of eight tokens in which both F1 and F2 measures were obtained.

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Fig. 8.6. % Change from Normal Condition in F2 and F1 in Bite-Block (BB), Bite-Block-Plus-Masking (B+M), and Masking (M) Conditions for Subject C4M



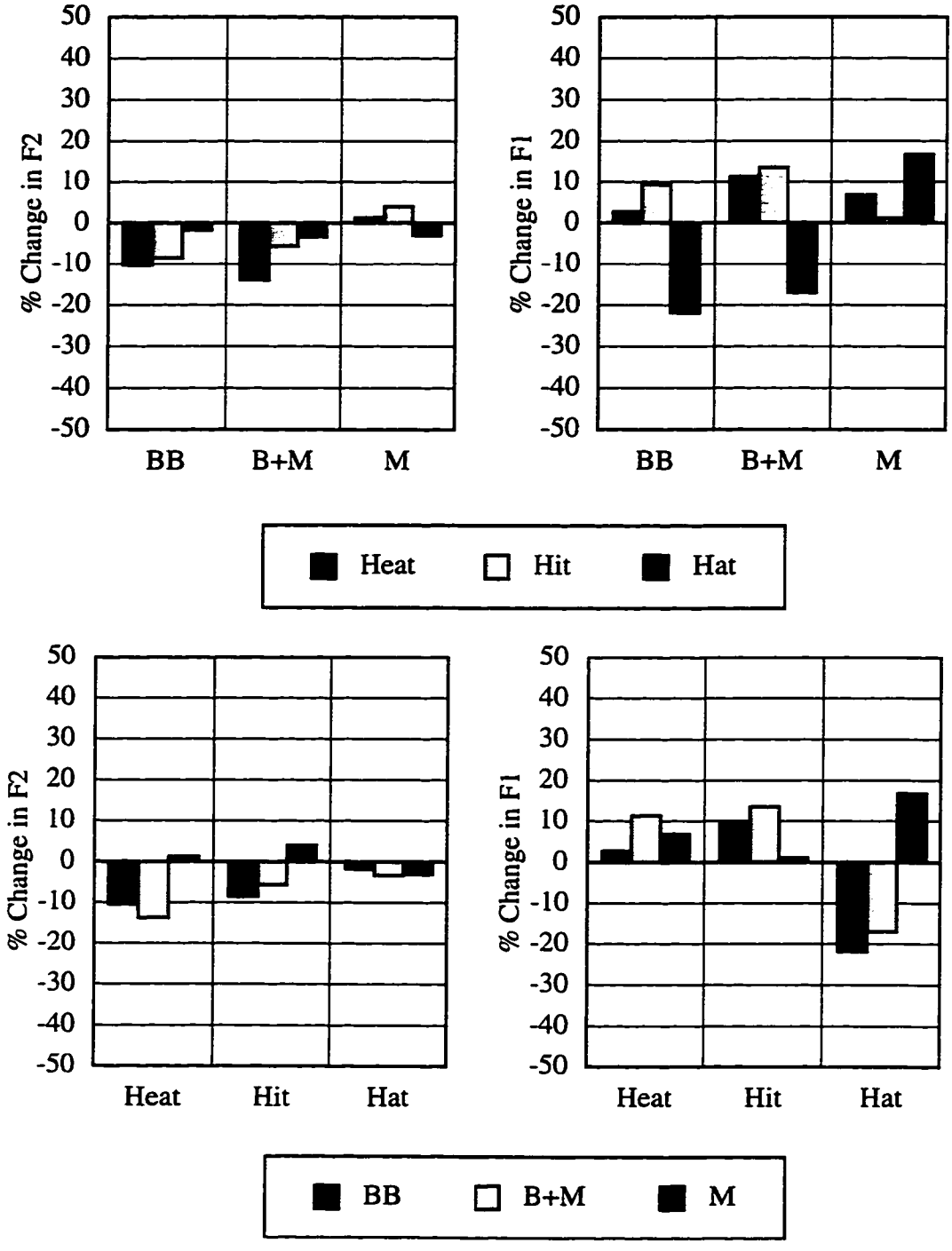
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Table 8.14.--Subject C5M: Means, Standard Deviations and Percent Change in Formants from Normal Condition to Test Conditions

Vowel	Condition	N	Mean F2	% Ch F2	Mean F1	% Ch F1	F2 St Dev	F1 St Dev
Heat	Normal	14	3530.00	***	441.00	***	151.00	75.80
	Bite Block	8	3164.00	-10.37	453.00	2.72	174.00	64.20
	Bite Block and Masking	17	3043.00	-13.80	491.00	11.34	349.00	25.40
	Masking	15	3574.00	1.25	471.00	6.80	144.00	36.00
Hit	Normal	15	2750.00	***	613.40	***	136.44	59.48
	Bite Block	14	2515.71	-8.52	671.00	9.39	221.60	36.55
	Bite Block and Masking	15	2595.20	-5.63	696.60	13.56	197.16	185.88
	Masking	14	2859.36	3.98	619.93	1.06	112.58	78.69
Hat	Normal	13	2552.46	***	1329.38	***	138.05	105.48
	Bite Block	10	2508.10	-1.74	1038.80	-21.86	152.23	148.02
	Bite Block and Masking	9	2467.22	-3.34	1104.56	-16.91	211.07	281.21
	Masking	15	2474.27	-3.06	1552.13	16.76	65.06	126.19

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Fig. 8.7. % Change from Normal Condition in F2 and F1 in Bite-Block (BB), Bite-Block-Plus-Masking (B+M), and Masking (M) Conditions for Subject C5M



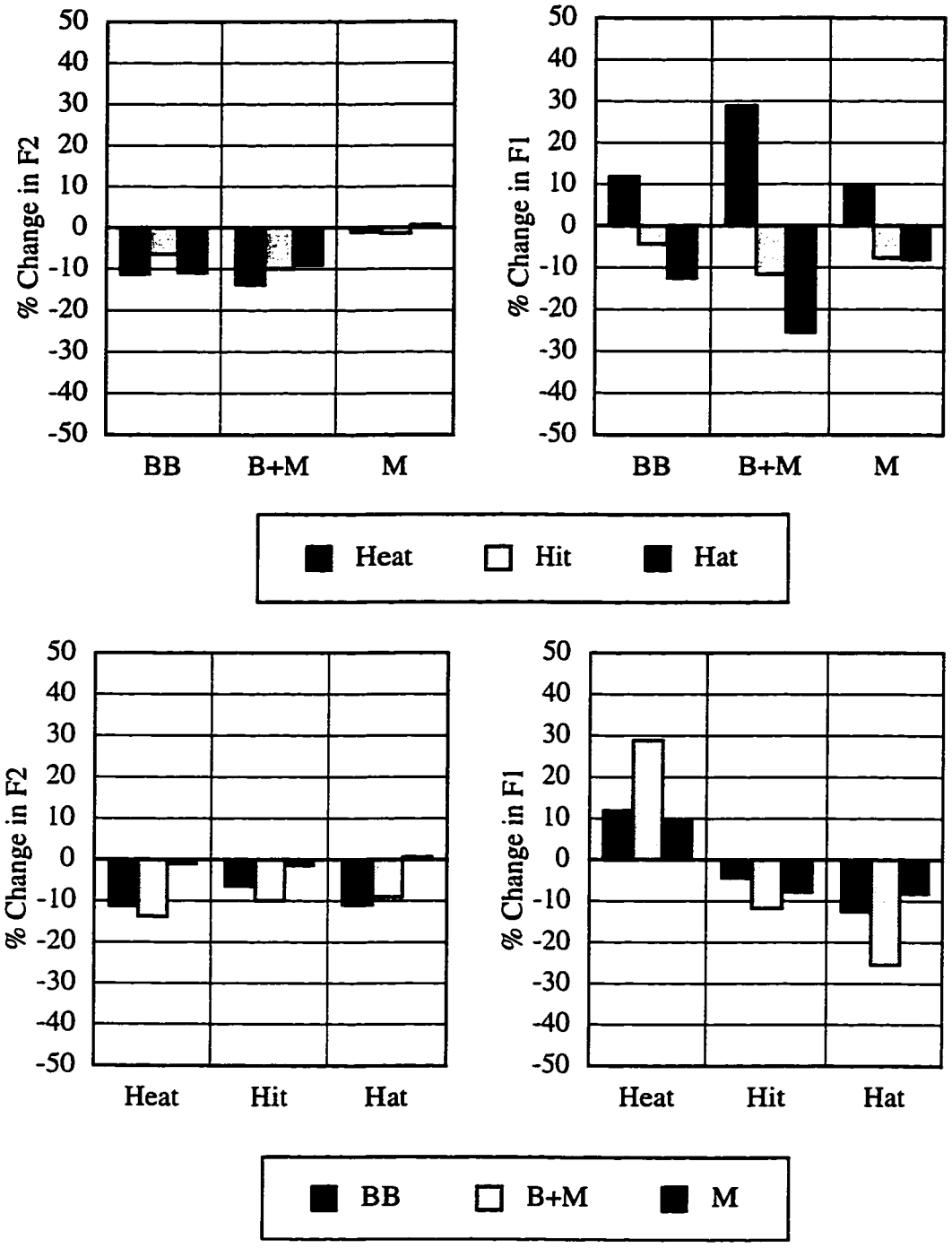
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Table 8.15.--Subject C6F: Means, Standard Deviations and Percent Change in Formants from Normal Condition to Test Conditions

Vowel	Condition	N	Mean F2	% Ch F2	Mean F1	% Ch F1	F2 St Dev	F1 St Dev
Heat	Normal	9	3445.33	***	436.33	***	221.45	21.78
	Bite Block	16	3058.88	-11.22	488.25	11.90	322.01	62.20
	Bite Block and Masking	13	2971.46	-13.75	562.39	28.89	289.73	79.99
	Masking	11	3410.55	-1.01	477.27	9.38	269.49	84.15
Hit	Normal	14	2739.71	***	845.21	***	125.13	143.47
	Bite Block	13	2564.00	-6.41	808.15	-4.38	187.06	80.38
	Bite Block and Masking	16	2465.44	-10.01	746.44	-11.69	133.04	76.98
	Masking	14	2701.29	-1.40	779.71	-7.75	290.10	186.97
Hat	Normal	16	2562.94	***	1338.56	***	61.47	69.94
	Bite Block	16	2283.19	-10.92	1171.88	-12.45	172.57	108.70
	Bite Block and Masking	10	2331.10	-9.05	997.20	-25.50	141.59	146.08
	Masking	11	2579.18	0.63	1230.18	-8.10	112.70	101.44

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Fig. 8.8. % Change from Normal Condition in F2 and F1 in Bite-Block (BB), Bite-Block-Plus-Masking (B+M), and Masking (M) Conditions for Subject C6F



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Magnitude of Change

To determine whether observed changes were statistically significant, three-way ANOVAs were performed for F2 and F1 for each child separately, treating each token from each condition as one sample, just as had been done with individual adults. Two-way ANOVAs, also identical to those performed for individual adults, were performed on the standard deviation values of F2 and F1 for each subject separately, using the twelve standard deviation values from three vowels in four conditions as the raw data. Three-way ANOVAs could not be performed because each cell had only one value. Thus the analyses were collapsed across one dimension, to perform two-way ANOVAs (BB x M; BB x V; and M x V). Two children, C1F and C4M, each were missing data for one test condition for one vowel. This had not occurred with the adults (although some were missing data from all conditions for one vowel). Missing cells made two-way and three-way ANOVAs impossible to use for those vowels. They were removed and analyzed by one-way ANOVAs for Condition, using F2 and F1 data from the conditions that remained. Those special F tables may be found in Appendices D1e-f and D4e-f. Analysis of standard deviation values could not be done for these vowels because data were limited to one value per cell. All other F tables for all the reported results that follow may be found for each child (C1-C6) as Appendices D1-D6, respectively.

F2

Table 8.16 summarizes the statistically significant changes in F2 frequency and F2 variability found for each individual child. Stars indicate presence and level of significant findings. Arrows indicate direction of change in formants.

A significant main effect of bite block for F2 was revealed for every child. The effect was highly significant ($p<.01$) for five of the six children. Further evidence was provided from the individual analyses of the vowels /i/ for C1F and /ae/ for C4M. (See Appendices D1e and D4e.) Significant effects of Condition on F2 were found in both cases.

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Subsequent Post Hoc Tukey HSD tests for unequal sample sizes revealed that the bite-block condition lowered F2 significantly from the normal condition in C4M's /ae/ productions and that both the bite-block and the bite-block-plus-masking conditions lowered F2 significantly in C1M's /i/ productions. (See Table 8.17.)

A significant main effect of masking on F2 was seen in one child only, C2M ($p<.01$). (See Table 8.16.)

A main effect of vowel was seen for every child and would, of course, be expected given the distinct F2 values of each vowel.

The children exhibited a trend toward greater F2 variability in test conditions. (See Table 8.16.). Three children exhibited a significant ($p<.05$) main effect of bite block; vowels spoken in bite-block conditions were more variable than those produced in non-bite-block conditions. Although a separate analysis of /i/ F2 standard deviation in subject C1F and /ae/ F2 standard deviation in subject C4M could not be performed because of the limited data, heat F2 variability was greater in the bite-block conditions (BB/i/ F2SD=379.08; B+M/i/ F2SD=259.97) than in the normal condition (/i/ F2SD=130.78) for C1F, but hat F2 variability was reduced in the bite-block condition (N/ae/ F2SD=119.07 vs. BB/ae/ F2SD=95.78) for C4M. These findings suggest vowel-specific bite-block effects, however, as will be seen in "Change Relative to Vowel Target" below, no bite-block-and-vowel interaction was found for F2 standard deviation.

Two children, C3F and C6F, exhibited a significant main effect of vowel on F2 variability. Subsequent Post Hoc Tukey HSD tests of differences between the mean standard deviations of F2 of each vowel were performed. (See Table 8.18.) Collapsed across conditions, F2 was significantly more variable for /i/ than for either /ae/ or /ɪ/ for C3F or /ae/ for C6F.

Only C1F exhibited an interaction of bite-block and masking effects on F2, collapsed across /ae/ and /ɪ/. (She was missing /i/ data.) (See Table 8.16.) Subsequent Post Hoc Tukey HSD tests for unequal sample sizes revealed that, except for the comparison of

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normal versus masking conditions, every other condition was significantly different ($p<.01$) from each other. (See Table 8.20.) These differences among conditions resulted from almost no effect of masking, a large effect of bite-block-plus-masking and an even greater effect of bite block. (See Figure 8.3.)

Table 8.16.--Summary of Significant Changes in F2 for Individual Children with Normal Hearing

Significant Changes in F2						
	C1F	C2M	C3F	C4M	C5M	C6F
Main Effect of Bite Block	↓ ★★	↓ ★★	↓ ★★	↓ ★	↓ ★★	↓ ★★
Main Effect of Masking		↑ ★★				
Main Effect of Vowel	★★	★★	★★	★★	★★	★★
Interaction of Bite Block and Masking	★★					
Significant Changes in F2 Standard Deviation						
	C1F	C2M	C3F	C4M	C5M	C6F
Main Effect of Bite Block	★	★[3]			★	
Main Effect of Masking						
Main Effect of Vowel			★★			★
Interaction of Bite Block and Masking						

★★=$p<.01$, ★=$p<.05$; ↑ = raised formant, ↓ = lowered formant

[3] The main effect of bite block on F2 standard deviation achieved significance at the $p<.05$ level in the bite-block x masking, two-way ANOVA, and at the $p<.01$ level in the bite-block x vowel, two-way ANOVA.

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Table 8.17.--Summary of Results of Post Hoc Tests of the Main Effect of Condition on F2 for Individual Children with Normal Hearing

C1F	/i/ F2		
	Normal 3474.64	Bite Block 2825.50	BB + Masking 3006.22
Normal v. Bite Block	p = .0002★★		
Normal v. BB + Masking	p = .0025★★		
Bite Block v. BB + Masking	p = .3669		
C4M	**/ae/ F2**		
	Normal 2443.20	Masking 2388.25	Bite Block 2268.00
Normal v. Masking	p = .6671		
Normal v. Bite Block	p = .0291★		
Masking v. Bite Block	p = .1633		

Table 8.18.--Summary of Results of Post Hoc Tests of the Main Effect of Vowel on F2 SD for Individual Children with Normal Hearing

C3F	Standard Deviation of F2		
	Heat 294.15	Hit 131.80	Hat 132.28
Heat v. Hat	p = .0094★★	Bite Block x Vowel Two-Way ANOVA	
Heat v. Hit	p = .0093★★	Bite Block x Vowel Two-Way ANOVA	
Heat v. Hat	p = .0032★★	Masking x Vowel Two-Way ANOVA	
Heat v. Hit	p = .0031★★	Masking x Vowel Two-Way ANOVA	
C6F	**Standard Deviation of F2**		
	Heat 275.67	Hit 183.83	Hat 122.09
Heat v. Hat	p = .0187★	Bite Block x Vowel Two-Way ANOVA	
Heat v. Hat	p = .0381★	Masking x Vowel Two-Way ANOVA	

★★ = p<.01, ★ = p<.05

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F1

Table 8.19 displays, in summary, the statistically significant changes in F1 frequency and F1 variability found for each individual child. A significant ($p<.01$) main effect of bite block for F1 was exhibited by four of the six children.

A majority of the children also showed a significant ($p<.01$) main effect of masking for F1.

A main effect of vowel was seen for every child and would be expected given the distinct F1 values characteristic of each vowel.

Only one child, C1F, showed an interaction of bite-block and masking effects on F1 ($p<.01$). Table 8.20 summarizes Post Hoc Tukey HSD tests for unequal sample sizes.

Table 8.19.--Summary of Significant Changes in F1 for Individual Children with Normal Hearing

Significant Changes in F1						
	C1F	C2M	C3F	C4M	C5M	C6F
Main Effect of Bite Block	↓ ★★		↓ ★★		↓ ★★	↓ ★★
Main Effect of Masking	↑ ★★	↑ ★★	↑ ★★		↑ ★★	↓ ★★
Main Effect of Vowel	★★	★★	★★	★★	★★	★★
Interaction of Bite Block and Masking	★★					
Significant Changes in F1 Standard Deviation						
	C1F	C2M	C3F	C4M	C5M	C6F
Main Effect of Bite Block						
Main Effect of Masking						
Main Effect of Vowel		★★	★★			★
Interaction of Bite Block and Masking						

★★=$p<.01$, ★=$p<.05$; ↑ = raised formant, ↓ = lowered formant

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Average F1 in every condition was significantly different from that in every other condition except for the comparison between the normal and the bite-block-plus-masking condition, which showed no significant change in the first formant. If one returns to Figure 8.3 it can be seen that some effects, collapsed across vowels, were reduced because formant changes for one vowel target were in the opposite direction of changes for another.

Table 8.20.--Summary of Post Hoc Tests of Significant Interactions of Bite-Block and Masking Effects (Collapsed Across Vowel) for Individual Children with Normal Hearing

Significant Differences in F2						
Condition	C1F	C2M	C3F	C4M	C5M	C6F
Normal vs. Bite Block	↓ ★★					
Normal vs. Bite Block and Masking	↓ ★★					
Normal vs. Masking						
Masking vs. Bite Block	★★					
Masking vs. Bite Block and Masking	★★					
Bite Block vs. Bite Block and Masking	★★					
Significant Differences in F1						
Condition	C1F	C2M	C3F	C4M	C5M	C6F
Normal vs. Bite Block	↓ ★★					
Normal vs. Bite Block and Masking						
Normal vs. Masking	↑ ★					
Masking vs. Bite Block	★★					
Masking vs. Bite Block and Masking	★					
Bite Block vs. Bite Block and Masking	★★					

★★=p<.01, ★=p<.05; ↑ = raised formant, ↓ = lowered formant

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No significant changes in variability for F1 were seen as a result of test conditions for any subject, however, three of the children showed a main effect of vowel. Subsequent Post Hoc Tukey HSD tests (See Table 8.21.) revealed, just as they had in the adults, the following trend for these children: F1 was most variable in hat, less so in hit, and least in heat, despite condition.

Table 8.21.--Summary of Results of Post Hoc Tests of the Main Effect of Vowel on F1 SD for Individual Children with Normal Hearing

C2M	Standard Deviation of F1		
	Heat 36.22	Hit 67.51	Hat 100.80
Heat v. Hat	p = .0030★★	Bite Block x Vowel Two-Way ANOVA	
Heat v. Hat	p = .0042★★	Masking x Vowel Two-Way ANOVA	
C3F	**Standard Deviation of F1**		
	Heat 59.81	Hit 136.68	Hat 167.78
Heat v. Hit	p = .0066★★	Bite Block x Vowel Two-Way ANOVA	
Heat v. Hat	p = .0013★★	Bite Block x Vowel Two-Way ANOVA	
Heat v. Hit	p = .0086★★	Masking x Vowel Two-Way ANOVA	
Heat v. Hat	p = .0017★★	Masking x Vowel Two-Way ANOVA	
C6F	**Standard Deviation of F1**		
	Heat 62.03	Hit 121.95	Hat 106.54
Heat v. Hit	p = .0435★	Bite Block x Vowel Two-Way ANOVA	

★★ = p<.01, ★ = p<.05

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Change Relative to Vowel Target

In the previous section, "Magnitude of Change," discussion was given to the results of ANOVAs that examined the effect of test conditions collapsed across vowels. Those same ANOVAs also revealed condition-by-vowel interactions that will be taken up here. It will be seen, both in figures and tests of significance, that some conditions affected some vowels more than others.

First, these effects have been presented graphically for each subject. Figures 8.9 - 8.20 follow. Two figures, identical to those that were displayed for each adult, are presented per page for each of the six children with normal hearing.

While the figures illustrate individual differences in the effect of test conditions and articulatory adjustments, one must return to the statistical tests of significance in order to make useful generalizations about conditions that changed the production of some vowels more than others.

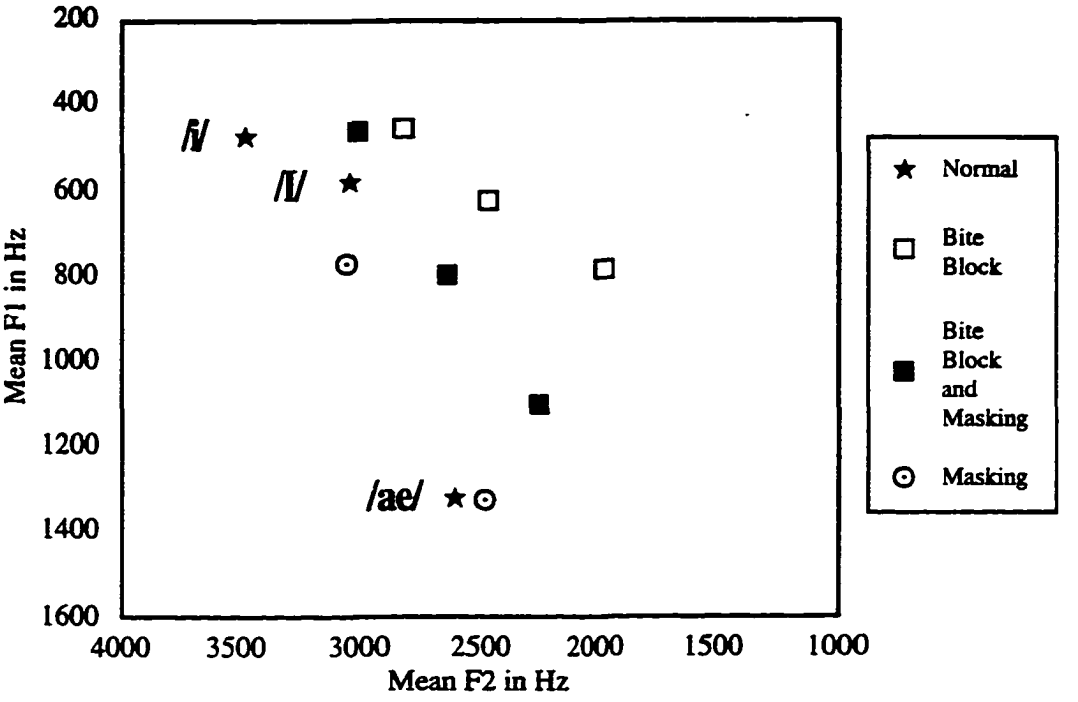
Few of the children showed significant interactions of condition and vowel effects on F2, although a majority exhibited them for F1. Summary tables are presented below to consolidate the detailed results. The reader will remember from earlier tables that no masking data for heat were available for subject C1F and no bite-block-plus-masking data for hat were available for C4M, so "N/A" will appear in parts of the tables where those data are missing. All F tables for all of the following reported results may be found for each child (C1-C6) as Appendices D1-D6, respectively.

F2

Few of the children showed significant interactions of condition and vowel on F2. Significant interactions and subsequent post hoc tests are summarized in Tables 8.22, 8.24, 8.25, and 8.26.

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Fig. 8.9. Subject C1F: Mean F1 by F2 Plot of Vowels in Each Condition



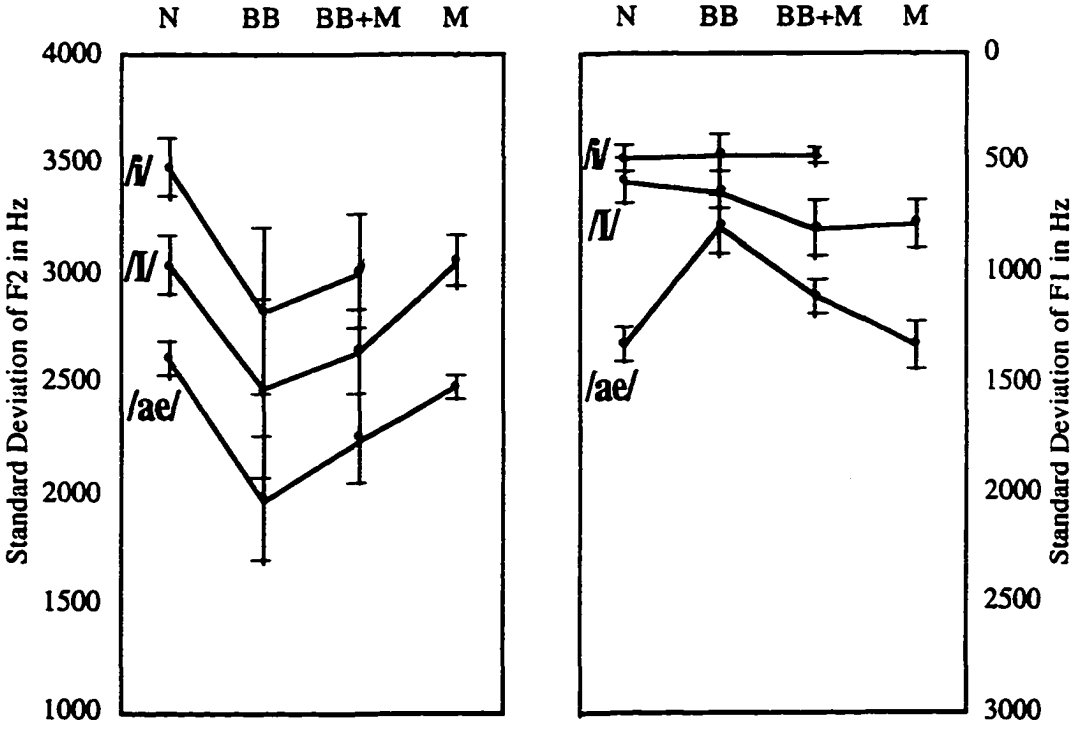
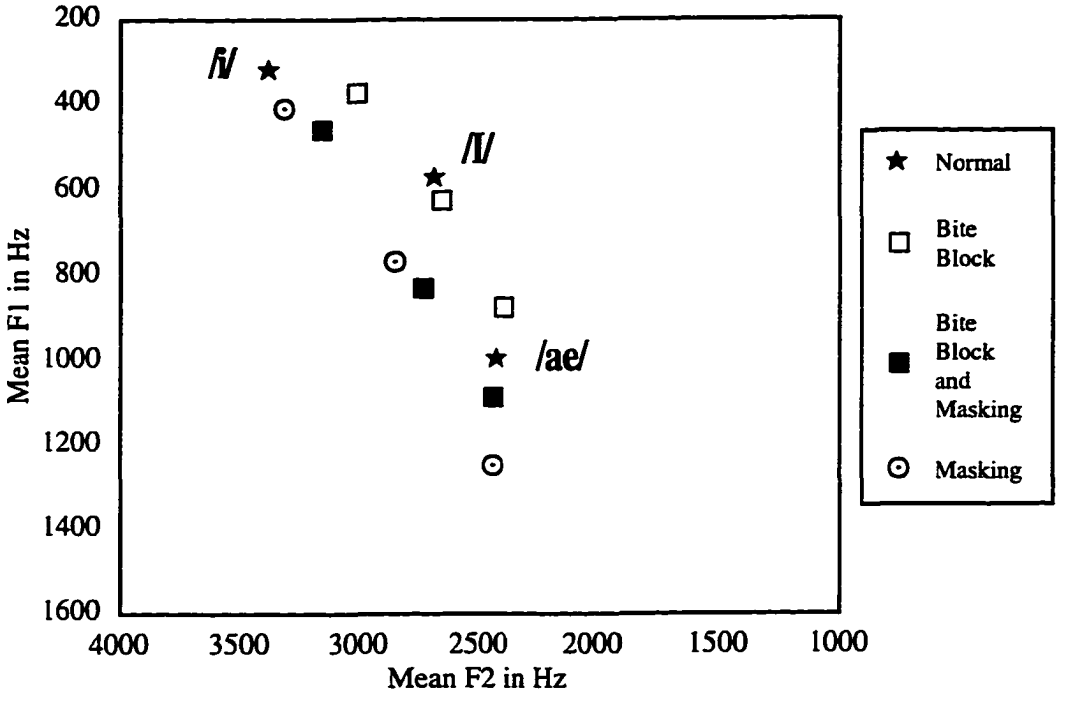


Fig. 8.10. C1F: Plots of One SD Above and Below Mean F2 and F1

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Fig. 8.11. Subject C2M: Mean F1 by F2 Plot of Vowels in Each Condition



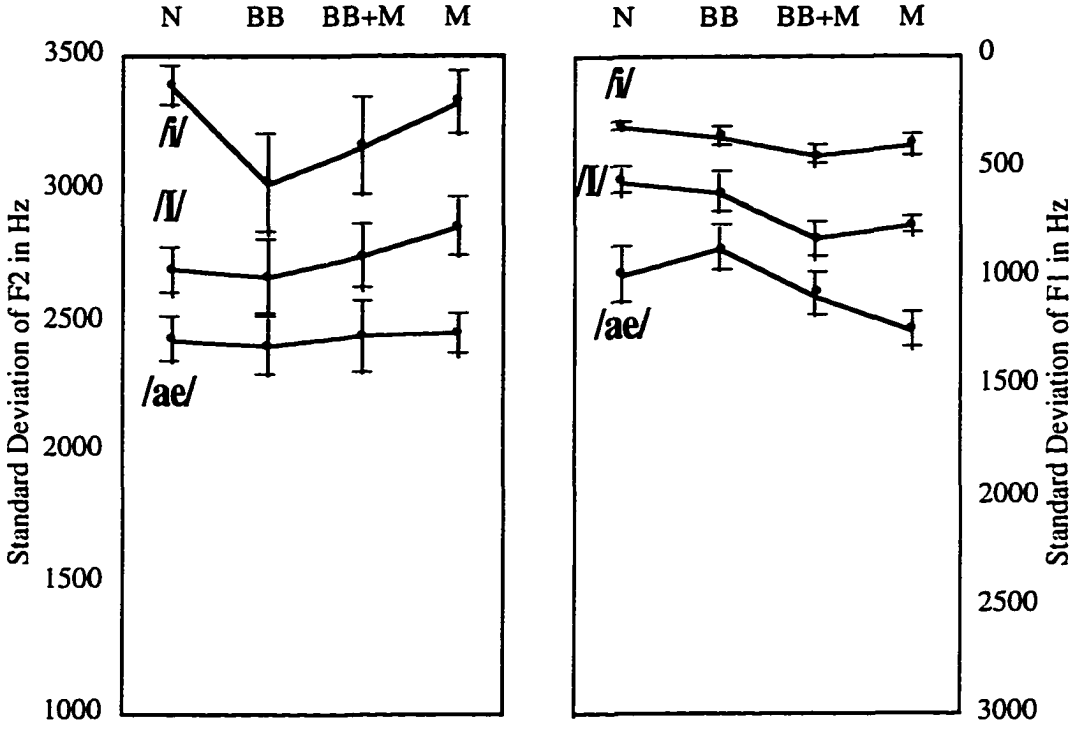
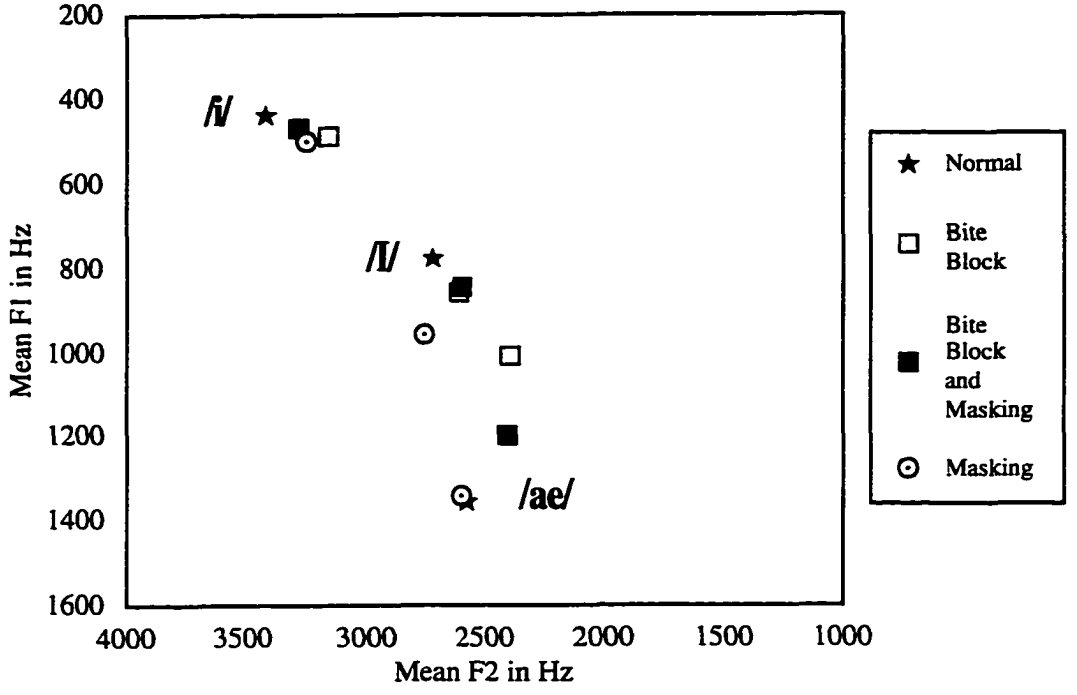


Fig. 8.12. C2M: Plots of One SD Above and Below Mean F2 and F1

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Fig. 8.13. Subject C3F: Mean F1 by F2 Plot of Vowels in Each Condition



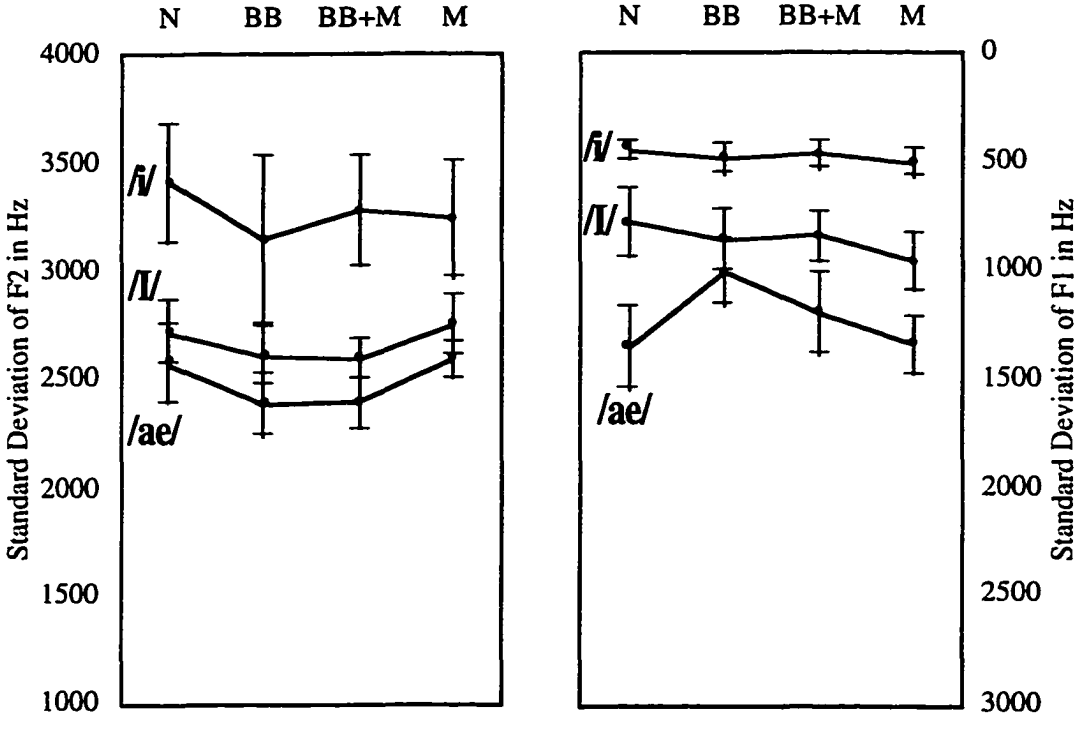
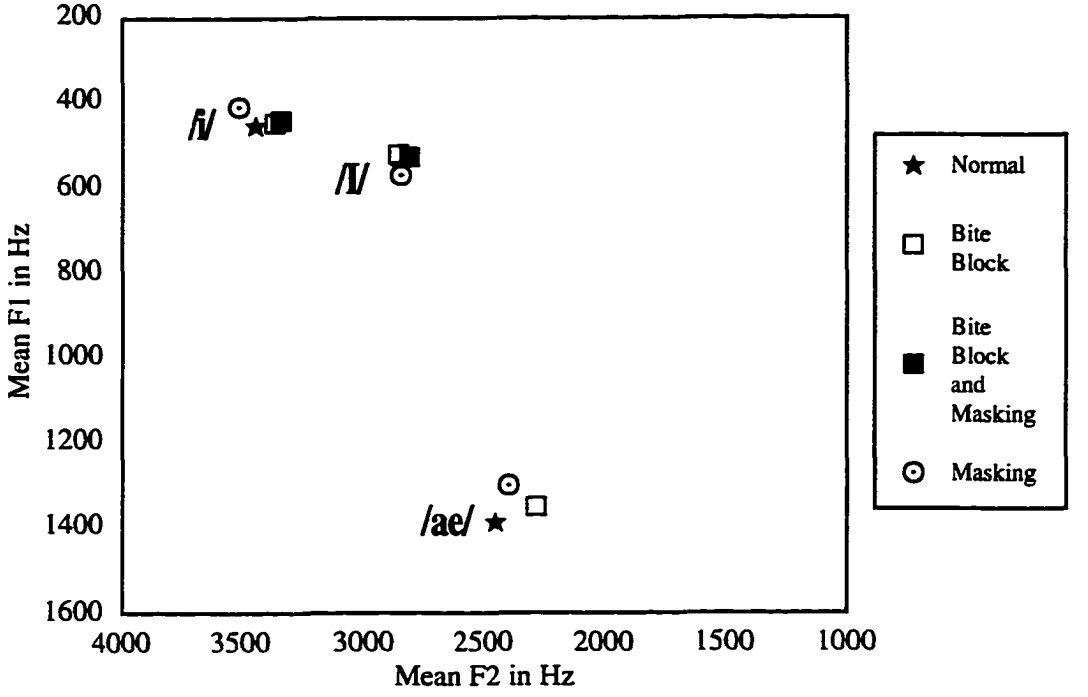


Fig. 8.14. C3F: Plots of One SD Above and Below Mean F2 and F1

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Fig. 8.15. Subject C4M: Mean F1 by F2 Plot of Vowels in Each Condition



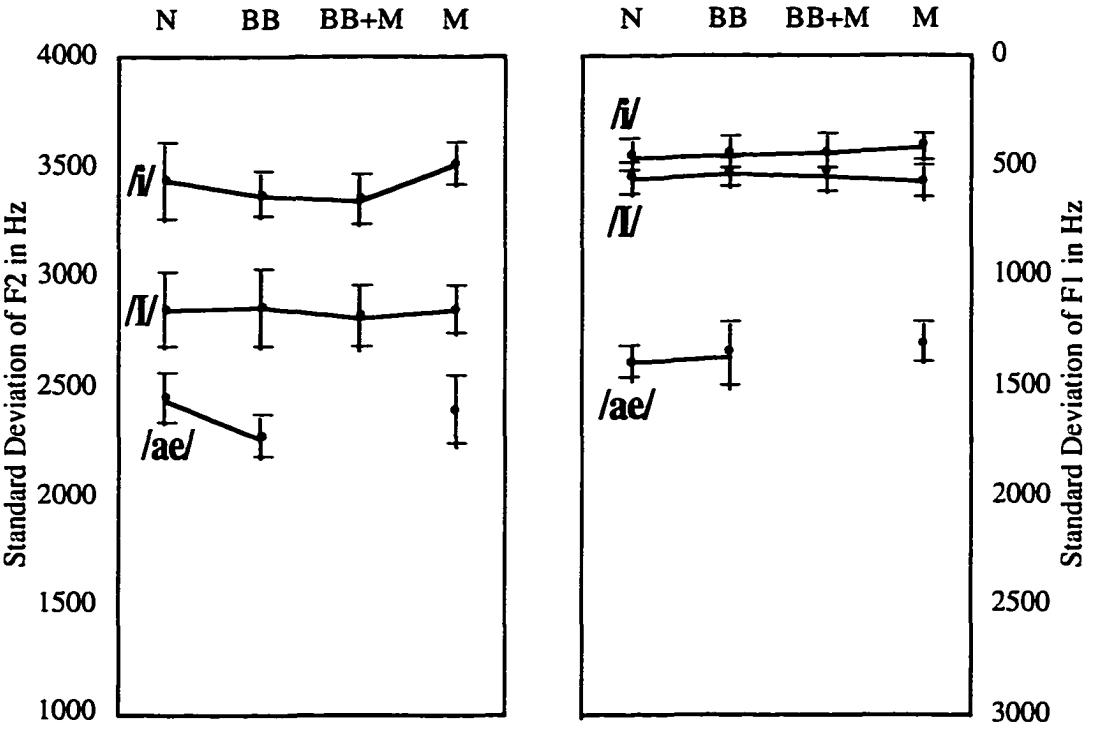
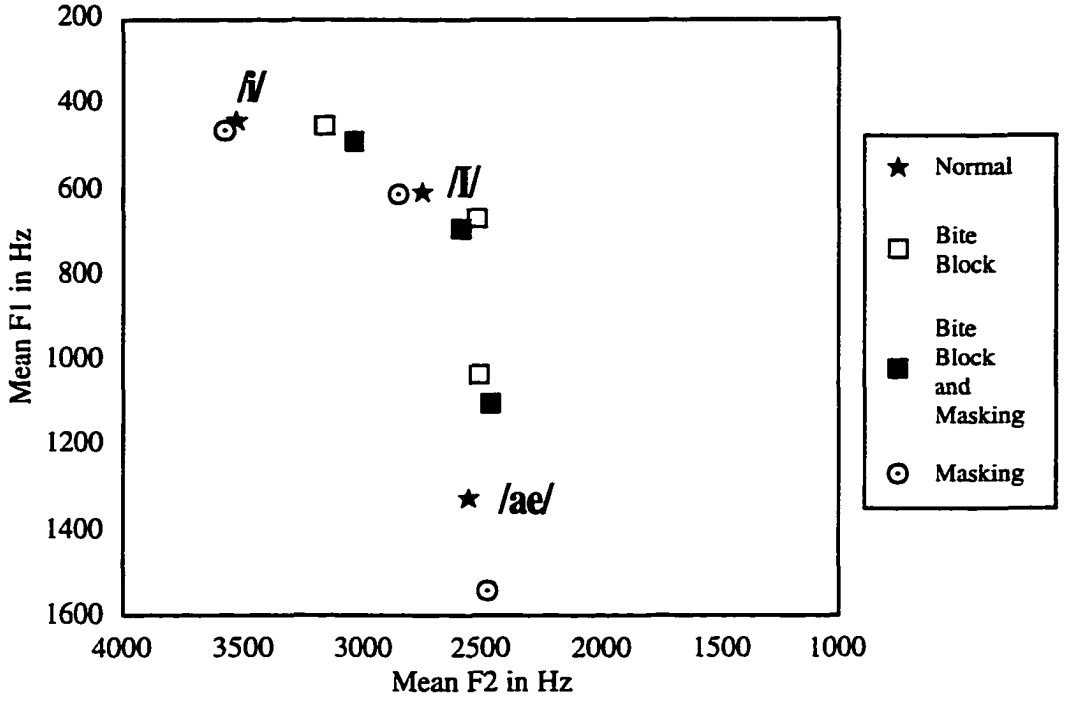


Fig. 8.16. C4M: Plots of One SD Above and Below Mean F2 and F1

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Fig. 8.17. Subject C5M: Mean F1 by F2 Plot of Vowels in Each Condition



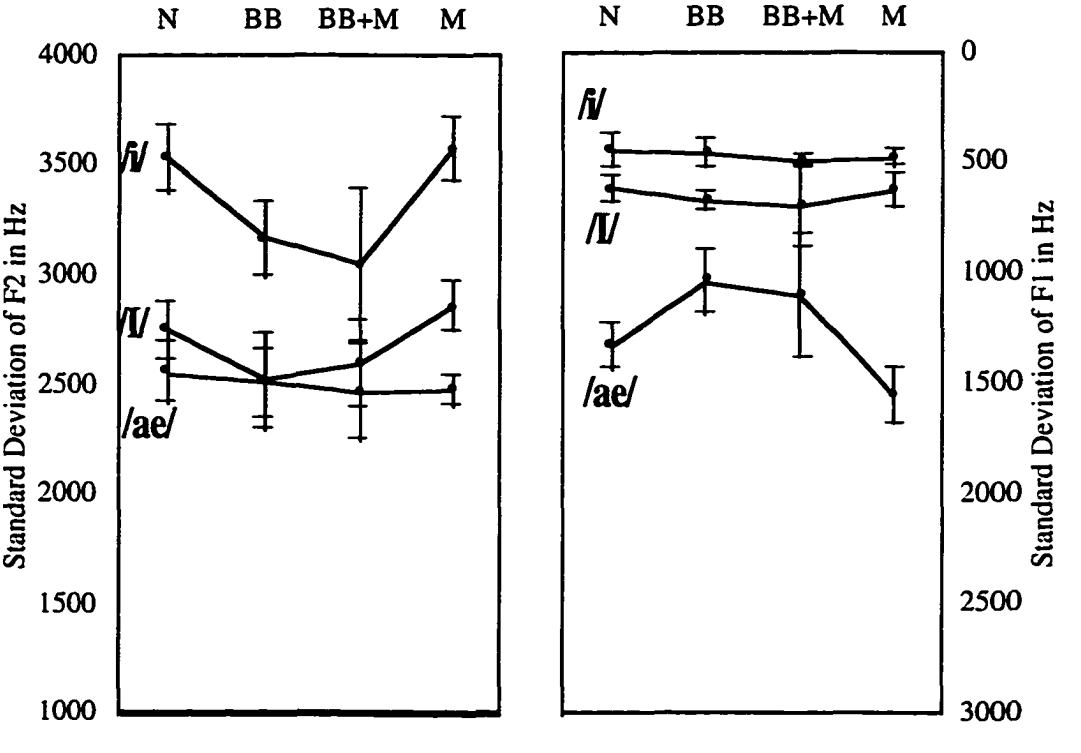
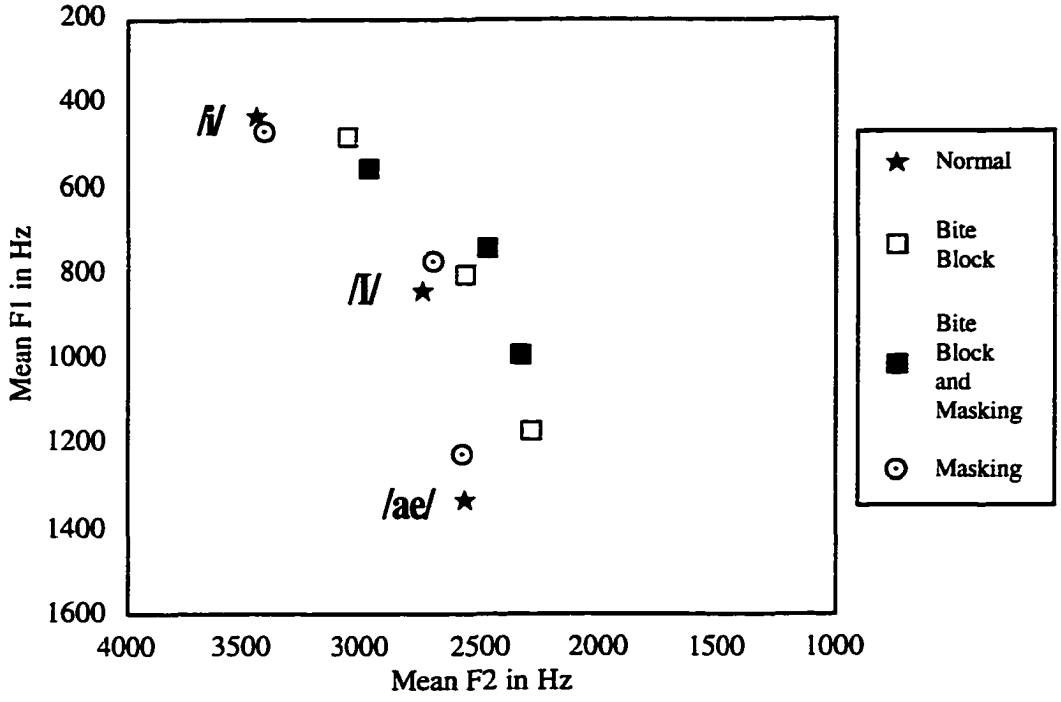


Fig. 8.18. C5M: Plots of One SD Above and Below Mean F2 and F1

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Fig. 8.19. Subject C6F: Mean F1 by F2 Plot of Vowels in Each Condition



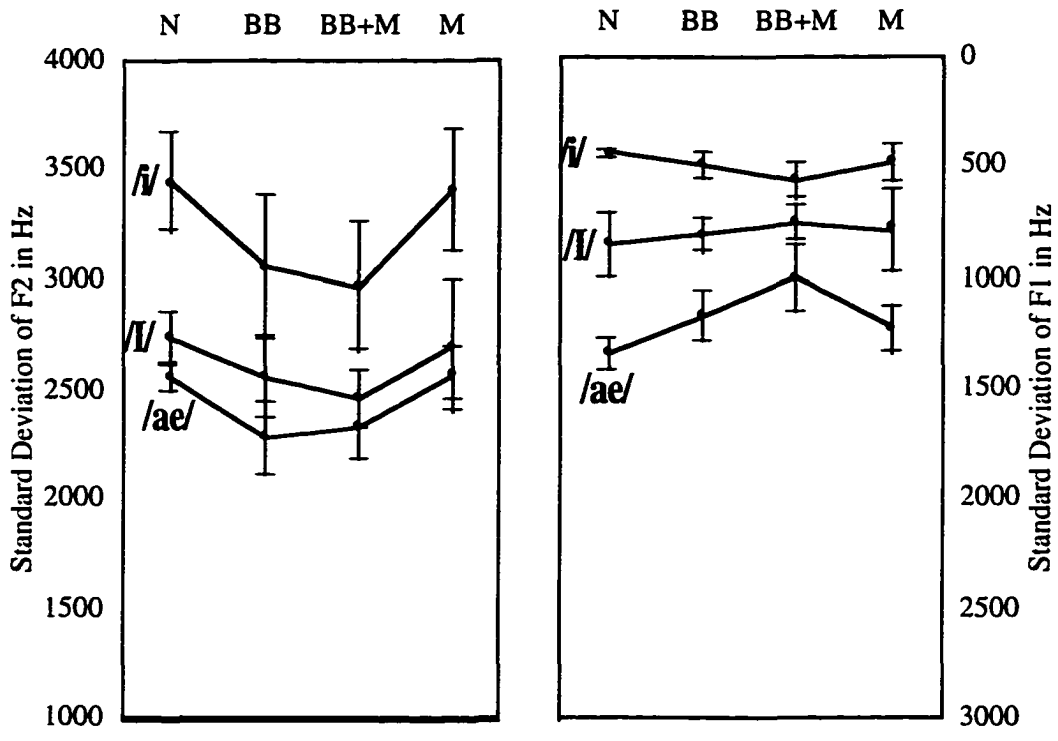


Fig. 8.20. C6F: Plots of One SD Above and Below Mean F2 and F1

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Table 8.22 shows that a significant interaction (a minimum of $p<.05$) of bite-block and vowel effects was found for half of the children. The details of this interaction may be examined in a summary of Post Hoc Tukey HSD tests for unequal sample sizes in Table 8.24. For those three children, the high vowel /i/ showed highly significant ($p<.01$) differences in F2 between conditions where a bite block was and was not used. C5M and C6F showed a highly significant effect of bite block on /I/, too. Only C6F showed an effect of bite block on /ae/.

Table 8.22 displays no significant interactions of masking and vowel effects in the children.

Table 8.22 shows a significant ($p<.05$) interaction of bite-block, masking and vowel effects for only one child. The details of this interaction may be examined in a summary of Post Hoc Tukey HSD tests for unequal sample sizes in Table 8.26. C2M exhibited significant differences between F2 in the normal and the bite-block conditions (BB and B+M) for the vowel /i/. The masking condition and the bite-block conditions (BB and B+M) also differed in that masking had little effect on F2. (See Figure 8.11.)

No significant interaction of bite block and vowel or masking and vowel was shown for F2 variability. (See Table 8.22.)

F1

Changes in F1, as a result of interactions of test condition and vowel target, were exhibited by a majority of the children. Significant interactions and subsequent post hoc tests are summarized in Tables 8.23, 8.24, 8.25, and 8.27.

Table 8.23 shows that a highly significant interaction ($p<.01$) of bite-block and vowel effects was found for a majority of the children. The details of this interaction may be examined in a summary of Post Hoc Tukey HSD tests for unequal sample sizes in Table 8.24. The children showed significant ($p<.01$) differences in hat F1 between conditions

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Table 8.22.--Summary of Significant Interactions of Effects on F2 in Individual Children with Normal Hearing

Significant Interactions of Effects on F2						
	C1F	C2M	C3F	C4M	C5M	C6F
Interaction of Bite Block and Vowel		★★			★★	★
Interaction of Masking and Vowel						
Interaction of Bite Block, Masking, and Vowel		★				
Significant Interactions of Effects on F2 Standard Deviation						
	C1F	C2M	C3F	C4M	C5M	C6F
Interaction of Bite Block and Vowel						
Interaction of Masking and Vowel						

Table 8.23.--Summary of Significant Interactions of Effects on F1 in Individual Children with Normal Hearing

Significant Interactions of Effects on F1						
	C1F	C2M	C3F	C4M	C5M	C6F
Interaction of Bite Block and Vowel	★★	★★	★★		★★	★★
Interaction of Masking and Vowel		★★			★	★★
Interaction of Bite Block, Masking, and Vowel	★★		★★			
Significant Interactions of Effects on F1 Standard Deviation						
	C1F	C2M	C3F	C4M	C5M	C6F
Interaction of Bite Block and Vowel						★
Interaction of Masking and Vowel						

★★=p<.01, ★=p<.05

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where a bite block was and was not used. In contrast, the higher vowels in heat and hit showed no significant effect of the bite block.

Table 8.23 displays a significant interaction (a minimum of $p<.05$) of masking and vowel effects in half of the children. The details of this interaction are in a summary of Post Hoc Tukey HSD tests for unequal sample sizes in Table 8.25. /ae/ was particularly affected by the masking condition.

Table 8.23 shows a significant ($p<.01$) interaction of bite-block, masking and vowel effects in only two children. The details of this interaction may be examined in a summary of Post Hoc Tukey HSD tests for unequal sample sizes in Table 8.27. Heat F1 in C1F and C3F were not affected significantly by test conditions. C1F exhibited substantially less successful adjustments for test conditions with hit. (See Figure 8.9.) C1F and C3F were little affected by masking for hat F1, but conditions employing a bite block produced significant changes, with the bite-block condition being more disruptive than the bite-block-plus-masking condition (cf Figures 8.9 and 8.13, respectively).

Table 8.23 shows that only C6F exhibited a significant ($p<.05$) interaction of bite block and vowel on F1 variability, but Post Hoc Tukey HSD tests revealed no meaningful findings.

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Table 8.24.--Summary of Post Hoc Tests of Significant Interactions of Bite-Block and Vowel Effects (Collapsed Across Masking) for Individual Children with Normal Hearing

Significant Differences in F2						
Condition and Vowel	C1F	C2M	C3F	C4M	C5M	C6F
No Bite-Block "heat" vs. Bite-Block "heat"	N/A	↓ ★★			↓ ★★	↓ ★★
No Bite-Block "hit" vs. Bite-Block "hit"					↓ ★★	↓ ★★
No Bite-Block "hat" vs. Bite-Block "hat"				N/A		↓ ★★
Significant Differences in F1						
Condition and Vowel	C1F	C2M	C3F	C4M	C5M	C6F
No Bite-Block "heat" vs. Bite-Block "heat"	N/A					
No Bite-Block "hit" vs. Bite-Block "hit"						
No Bite-Block "hat" vs. Bite-Block "hat"	↓ ★★	↓ ★★	↓ ★★	N/A	↓ ★★	↓ ★★

Table 8.25.--Summary of Post Hoc Tests of Significant Interactions of Masking and Vowel Effects (Collapsed Across Bite Block) for Individual Children with Normal Hearing

Significant Differences in F2						
Condition and Vowel	C1F	C2M	C3F	C4M	C5M	C6F
No Masking "heat" vs. Masking "heat"	N/A					
No Masking "hit" vs. Masking "hit"						
No Masking "hat" vs. Masking "hat"				N/A		
Significant Differences in F1						
Condition and Vowel	C1F	C2M	C3F	C4M	C5M	C6F
No Masking "heat" vs. Masking "heat"	N/A	↑ ★				
No Masking "hit" vs. Masking "hit"		↑ ★★				
No Masking "hat" vs. Masking "hat"		↑ ★★		N/A	↑ ★★	↓ ★★

★★=p<.01, ★=p<.05; ↑ = raised formant, ↓ = lowered formant

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Table 8.26.--Summary of Post Hoc Tests of Significant Interactions of Bite-Block, Masking, and Vowel Effects on F2 for Individual Children with Normal Hearing

Significant Differences in F2						
Condition and Vowel	C1F	C2M	C3F	C4M	C5M	C6F
Normal "heat" vs. Bite-Block "heat"	N/A	★★				
Normal "heat" vs. Bite-Block-plus-Masking "heat"	N/A	★				
Normal "heat" vs. Masking "heat"	N/A					
Masking "heat" vs. Bite-Block "heat"	N/A	★★				
Masking "heat" vs. Bite-Block-plus-Masking "heat"	N/A					
Bite Block "heat" vs. Bite-Block-plus-Masking "heat"	N/A					
Normal "hit" vs. Bite-Block "hit"						
Normal "hit" vs. Bite-Block-plus-Masking "hit"						
Normal "hit" vs. Masking "hit"						
Masking "hit" vs. Bite-Block "hit"						
Masking "hit" vs. Bite-Block-plus-Masking "hit"						
Bite Block "hit" vs. Bite-Block-plus-Masking "hit"						
Normal "hat" vs. Bite-Block "hat"				N/A		
Normal "hat" vs. Bite-Block-plus-Masking "hat"				N/A		
Normal "hat" vs. Masking "hat"				N/A		
Masking "hat" vs. Bite-Block "hat"				N/A		
Masking "hat" vs. Bite-Block-plus-Masking "hat"				N/A		
Bite Block "hat" vs. Bite-Block-plus-Masking "hat"				N/A		

★★=p<.01, ★=p<.05; direction of change illustrated in Figures 8.21-8.23

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Table 8.27.--Summary of Post Hoc Tests of Significant Interactions of Bite-Block, Masking, and Vowel Effects on F1 for Individual Children with Normal Hearing

Significant Differences in F1						
Condition and Vowel	C1F	C2M	C3F	C4M	C5M	C6F
Normal "heat" vs. Bite-Block "heat"	N/A					
Normal "heat" vs. Bite-Block-plus-Masking "heat"	N/A					
Normal "heat" vs. Masking "heat"	N/A					
Masking "heat" vs. Bite-Block "heat"	N/A					
Masking "heat" vs. Bite-Block-plus-Masking "heat"	N/A					
Bite Block "heat" vs. Bite-Block-plus-Masking "heat"	N/A					
Normal "hit" vs. Bite-Block "hit"						
Normal "hit" vs. Bite-Block-plus-Masking "hit"	★★					
Normal "hit" vs. Masking "hit"	★★		★			
Masking "hit" vs. Bite-Block "hit"						
Masking "hit" vs. Bite-Block-plus-Masking "hit"						
Bite Block "hit" vs. Bite-Block-plus-Masking "hit"	★					
Normal "hat" vs. Bite-Block "hat"	★★		★★	N/A		
Normal "hat" vs. Bite-Block-plus-Masking "hat"	★★			N/A		
Normal "hat" vs. Masking "hat"				N/A		
Masking "hat" vs. Bite-Block "hat"	★★		★★	N/A		
Masking "hat" vs. Bite-Block-plus-Masking "hat"	★★			N/A		
Bite Block "hat" vs. Bite-Block-plus-Masking "hat"	★★		★	N/A		

★★=p<.01, ★=p<.05; direction of change illustrated in Figures 8.21-8.23

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Summary

Tables 8.28 - 8.31 facilitate the comparison of bite-block, masking, and bite-block-plus-masking effects on all dependent variables, to show patterns revealed by the majority of individual talkers within each subject group. Columns for results from subsequent chapters appear in gray now.

The data from individual children revealed that:

A. the bite block lowered F2 for every vowel. (See Table 8.28.) A significant (at least p=.05 or greater) main effect of bite block was reached by every child. These findings are virtually identical to the findings in the adults, although percent-change ranges were larger in the children. Half of the children also exhibited a significant bite-block-by-vowel interaction wherein the close vowels /i/ and /I/ appeared to be more often affected by the bite block. The findings suggest that close vowel targets may have posed a greater compensation challenge for the children than for the adults. The bite-block raised F1 for /i/ and /I/, but lowered it for /ae/. Again, the results are identical to those of the adults, despite the use of 20-mm bite blocks with the adults and 10-mm bite blocks with the children. This finding suggests that the bite blocks chosen for each subject group resulted in a less-than-normal interincisal distance for the vowel /ae/, as predicted by computer simulation. The range of percent change was larger in the children, as it was for F2. A significant (at least p=.05 or greater) main effect of bite block on F1 was reached by a majority of children, as was a significant bite-block-by-vowel interaction : /ae/ F1 was most often affected by the bite block.

B. masking resulted in no consistent direction of change in F2. /i/ F2 was lowered, /I/ F2 was raised and /ae/ F2 was raised as often as it was lowered, leaving no clear impression of direction of change. For the adults, masking effects had mirrored bite-block effects and both resulted in significant lowering in F2. For the children, the masking effect did not resemble the effect of bite block, nor did it result in significant changes to F2. While the range of percent change had been larger for the children than

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for the adults in bite-block conditions, in the masking condition the ranges were comparable. The effect of masking on F1 was different. /i/ and /I/ F1 were raised, as they were for the adults, but direction of change for /ae/ F1 remained unclear, as it had for /ae/ F2. Range of percent change was again larger in the children than in the adults and a main effect of masking on F1 was reached for a majority of the children. A significant masking-by-vowel interaction in half the children suggested that /ae/ F1 was differentially affected by masking. /i/ and /I/ F1 were most often affected in the masking condition in the adults. Masking effects on F1 closely resembled bite-block effects on F1, as they had in the adults, but the minimal effect on F2 distinguishes the children from the adults overall.

C. the bite-block-plus-masking condition lowered F2 in all vowels. This direction of change was identical to that in the bite-block condition, but the amount of change was not significant, as it had been for the bite block alone. /i/ and /I/ F1 were raised and /ae/ lowered in the bite-block-plus-masking condition, identical to the results for the bite block. However, significant interactions of bite block and masking were not found for the majority of the children, nor were interactions of bite block and masking and vowel, for either F2 or F1. Only C2M exhibited a significant interaction of bite block, masking and vowel on F2. (See Table 8.22.) C1F and C3F exhibited significant interactions of bite block, masking and vowel on F1. (See Table 8.23.) Figures 8.21 - 8.23 provide an overview of changes in both formants for each vowel in each child. Where children exhibited a significant interaction of bite block, masking and vowel, post hoc tests were conducted for differences. (See Tables 8.26 and 8.27.) Those post hoc tests that showed significant differences between normal and test conditions are identified by stars in Figures 8.21 - 23. Thus the reader will find significant results for C2M for F2 and C1F and C3F for F1. The only other significant results placed there are for C1F in the plot for /i/ (Figure 8.21) and C4F in the plot for /ae/ (Figure 8.23). The reader will remember that each of these children were missing data from one

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condition for these vowels and a one-way analysis of variance by condition was conducted for each vowel. Where a significant effect of condition and subsequent post hoc tests revealed significant differences between normal and test conditions (Table 8.17), the results were included. Therefore, Figure 8.21 includes significant findings for C1F for /ʏ/ and Figure 8.23 includes a significant finding for C4M for F2. In general, the bite-block-plus-masking results with the children do not suggest that the effects of the bite block were more detrimental in the presence of masking.

D. bite-block conditions produced significantly greater F2 variability in half of the children, but no systematic changes were seen in F1 variability as a result of test conditions. (See Table 8.31.) Three children and all the adults showed a significant main effect of vowel on F1; it was most variable in hat, less in hit, and least in heat collapsed across condition.

E. individual subjects varied in their ability to compensate in test conditions.

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Table 8.28.--Summary of Bite-Block Effects on F2 and F1 for the Majority of Individual Subjects

	Adults with Normal Hearing	**Children with Normal Hearing**	Adults with Profound Hearing Loss	Adults with Severe Hearing Loss
F2 Direction of Change: heat hit hat	 lowered lowered lowered	 lowered lowered lowered		
Range of % Change	.23 - 16.58%	.22 - 24.48		
Main Effect of Bite Block	★★(all)	★/★★(all)		
BB-by-Vowel Interaction	★/★★	★/★★(half)		
Details of Interaction:	individual variation in affected vowel targets	/i/ most often affected; /I/ also, but less often		
F1 Direction of Change: heat hit hat	 raised raised lowered	 raised raised lowered		
Range of % Change	.38 - 24.25%	1.85 - 40.43		
Main Effect of Bite Block	★/★★	★/★★		
BB-by-Vowel Interaction	★/★★(all)	★/★★		
Details of Interaction:	hat most often affected	hat most often affected		

★★=p<.01, ★=p<.05

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Table 8.29.--Summary of Masking Effects on F2 and F1 for the Majority of Individual Subjects

	Adults with Normal Hearing	**Children with Normal Hearing**	Adults with Profound Hearing Loss	Adults with Severe Hearing Loss
F2 Direction of Change: heat hit hat	 lowered lowered lowered	 lowered raised unclear		
Range of % Change	.43 - 5.4%	.15 - 6.09		
Main Effect of Masking	★/★★			
M-by-Vowel Interaction	★/★★			
Details of Interaction:	N1M and N6M particularly affected by masking for all vowels			
F1 Direction of Change: heat hit hat	 raised raised raised	 raised raised unclear		
Range of % Change	.22 - 18.8%	.35 - 33.68		
Main Effect of Masking	★/★★(all)	★/★★		
M-by-Vowel Interaction	★/★★	★/★★(half)		
Details of Interaction:	heat and hit most often affected	hat most often affected		

★★=p<.01, ★=p<.05

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Table 8.30.--Summary of Bite-Block-plus-Masking Effects on F2 and F1 for the Majority of Individual Subjects

	Adults with Normal Hearing	**Children with Normal Hearing**	Adults with Profound Hearing Loss	Adults with Severe Hearing Loss
F2 Direction of Change:				
heat	lowered	lowered		
hit	lowered	lowered		
hat	lowered	lowered		
Range of % Change	.66 - 16.71%	.52 - 13.88		
Interaction of BB and M				
Interaction of BB and M and Vowel	★/★★			
Details of Interactions:				
heat	affected more by B+M than by BB or M alone			
hit	no overall pattern			
hat	affected more by B+M than by BB or M alone			
F1 Direction of Change:				
heat	raised	raised		
hit	raised	raised		
hat	raised	lowered		
Range of % Change	.44 - 36.67%	1.9 - 45.41		
Interaction of BB and M	★/★★			
Interaction of BB and M and Vowel	★/★★			
Details of Interactions:				
in general	M and B+M more detrimental than BB alone			
heat	little effect			
hit	B+M detrimental for N4F and N6M			
hat	BB and B+M more detrimental than masking alone			

★★=p<.01, ★=p<.05

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Table 8.31.--Summary of All Test Effects on F2 and F1 Variability for the Majority of Individual Subjects

	Adults with Normal Hearing	**Children with Normal Hearing**	Adults with Profound Hearing Loss	Adults with Severe Hearing Loss
Main Effect of Bite Block		↑ ★/★★(half)		
Interaction of BB and V				
Main Effect of Masking				
Interaction of M and V				
Interaction of BB and M				
Main Effect of Vowel				
Details of Interactions:				
Main Effect of Bite Block				
Interaction of BB and V				
Main Effect of Masking				
Interaction of M and V				
Interaction of BB and M				
Main Effect of Vowel	★/★★(all)	★/★★(half)		
Details of Interactions:				
heat	least variability	least variability		
hit	more variability	more variability		
hat	greatest variability	greatest variability		

★★=p<.01, ★=p<.05; ↑ = increased variability, ↓ = decreased variability

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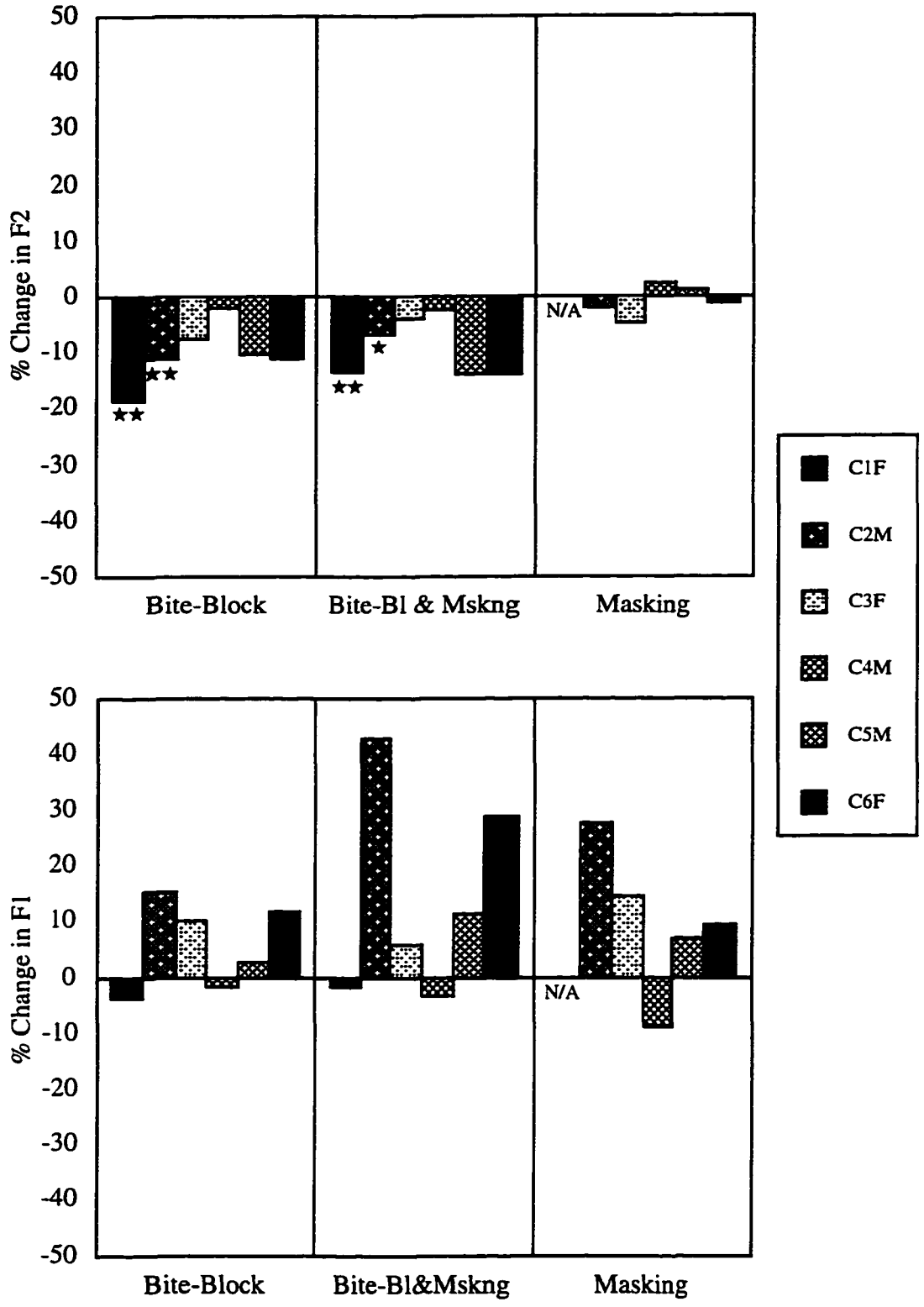


Fig. 8.21. Overview of Changes in F2 and F1 in /i/ for Each Child with Normal Hearing

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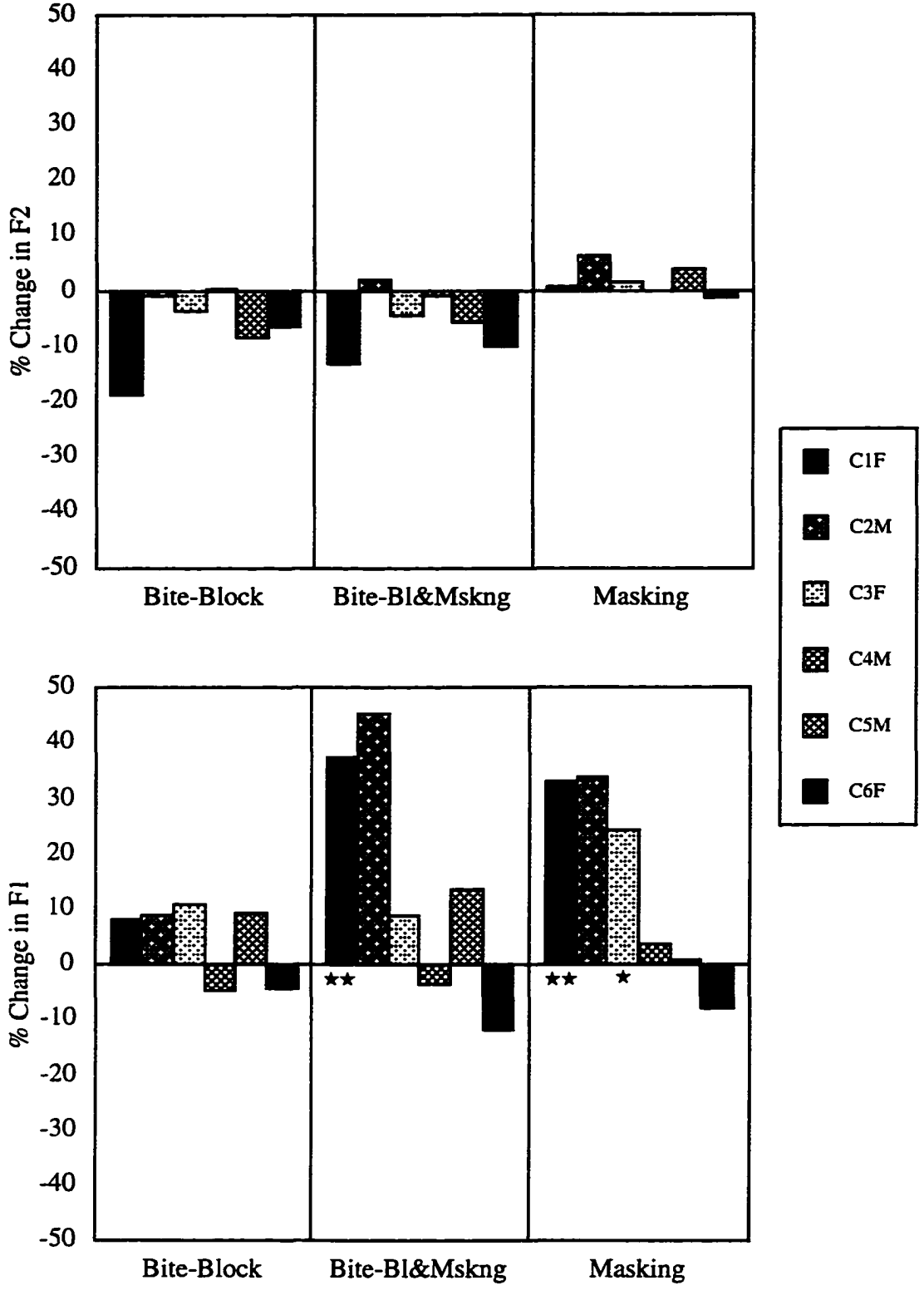


Fig. 8.22. Overview of Changes in F2 and F1 in /I/ for Each Child with Normal Hearing

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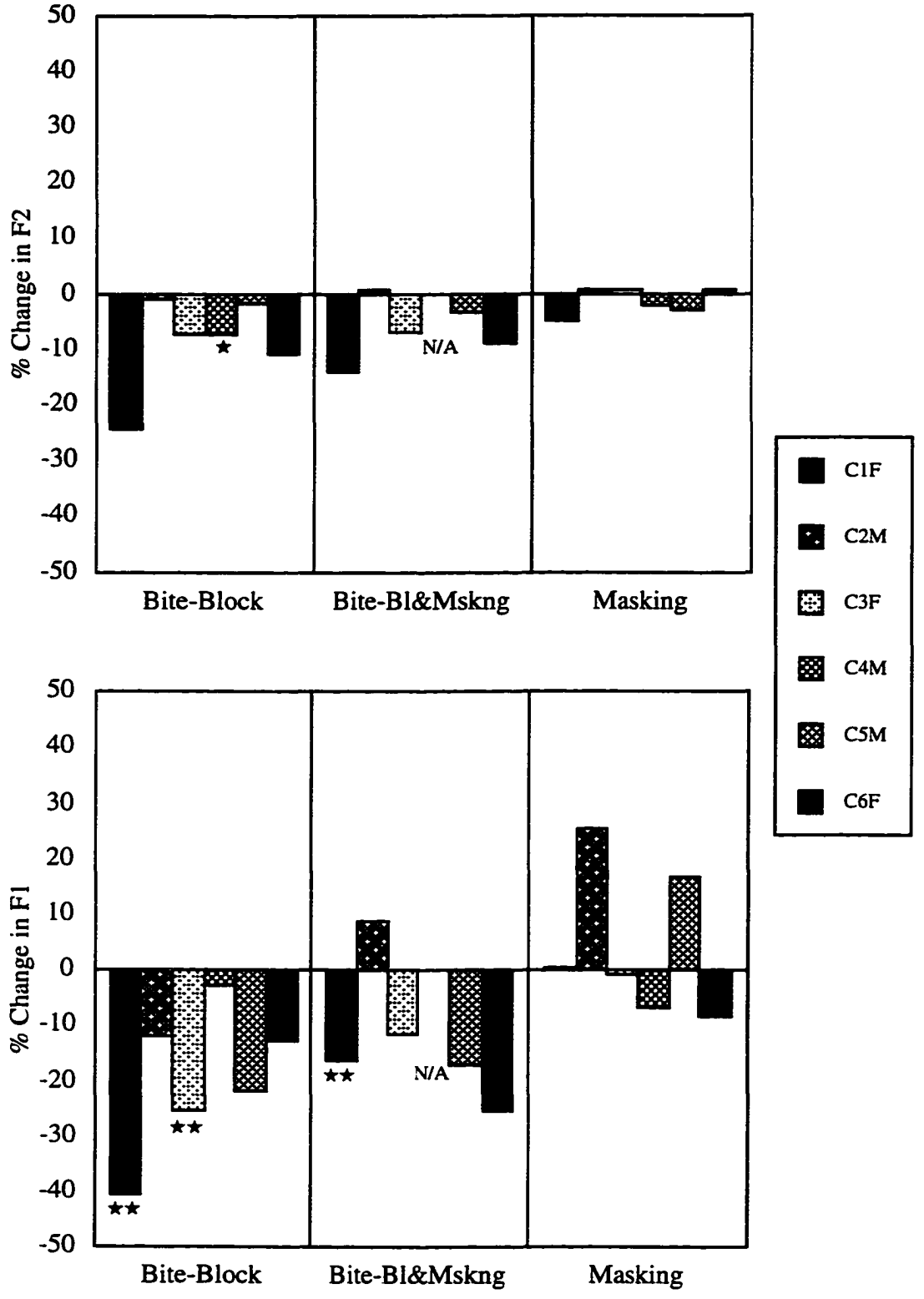


Fig. 8.23. Overview of Changes in F2 and F1 in /ae/ for Each Child with Normal Hearing

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Summary of Results from the Children with Normal Hearing

Bite-Block Effects

Tables 8.4 and 8.28 illustrate the overall summary statements made here. The bite-block lowered F2, as predicted by computer simulation. The group showed a significantly lowered F2 for every vowel, and every individual subject showed a significant main effect of bite block collapsed across vowels. Although all vowels showed an effect, a bite-block-by-vowel interaction was shown for half of the individual subjects, revealing that the close vowels /i/ and /I/ were more often affected by the bite block in some of the children.

Bite-block conditions raised F1 for heat and hit, as predicted by computer simulation for a greater-than-normal interincisal distance. F1 was lowered in hat. Computer simulation also predicted that F1 would be lowered for a less-than-normal interincisal distance. The 10-mm bite block used with children appeared to have created a less-than-normal interincisal distance for /ae/. F1 for /ae/ was lowered significantly for the group and a main effect of bite block was found for a majority of individual talkers. A bite-block-by-vowel interaction was shown for most of the individual children and it also revealed that hat was most often affected.

Comparing findings across subject groups, results for F2 were very similar in the adults and the children. A greater number of significant findings for the children as a group and the bite-block-by-vowel interaction in half of the children, revealing that close vowels were most often affected by the bite block, suggest that bite-block effects on F2 were greater in the children. Results for F1 suggest that the 20-mm bite block produced a greater-than-normal interincisal distance on average for the group of adults, but it lowered F1 in a majority of individual adult talkers. The 10-mm bite block more consistently produced a less-than-normal interincisal distance in the children. Despite the difference in bite-block size, both subject groups demonstrated less compensation for a bite block when /ae/ was the target.

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Masking Effects

Tables 8.5 and 8.29 illustrate the overall summary statements made here. Masking produced very small changes in F2 that were of no clear direction. The changes were not significant for the group or for individual children, in contrast to the bite-block condition that produced significant changes.

Masking raised F1 for every vowel in the group. Most of the individual talkers exhibited a raised F1 for heat and hit, but the pattern was unclear for hat. While there were no significant findings for the group, most individuals displayed a significant main effect of masking and half of the children exhibited a masking-by-vowel interaction that showed that hat was most often affected by masking.

The adults and the children displayed quite different effects of masking. For the adults, masking mirrored bite-block effects in direction. The group exhibited a significant effect on /i/ F2, but a majority of the adults showed significant main effects of masking on both F2 and F1 collapsed across vowels. Conversely, the children showed almost no effect of masking on F2 as a group or as individuals, however, a majority of individual children showed an effect of masking on F1 for hat.

Bite-Block-Plus-Masking Effects

Tables 8.6 and 8.30 illustrate the overall summary statements made here. The combination of bite block and masking lowered F2. The condition significantly lowered F2 for all vowels in the group, but failed to do so in a majority of individual talkers.

The bite-block-plus-masking condition raised F1 for /i/ and /I/, but lowered /ae/ F1 significantly in the group. Individual talkers displayed the same direction of change, but, again failed to reveal any significant changes.

Comparing subject groups, the direction and magnitude of the F2 changes, resulting from the bite-block-plus-masking effects, were quite similar. However, a majority of adult talkers exhibited an interaction of bite block and masking and vowel, while individual

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children did not. F1 was significantly lowered in /ae/ in the group of children, but significantly raised in /I/ for the group of adults. Again, most of the adults showed a significant interaction of bite block and masking across vowels, but most of the children did not. This suggests that, overall, and unexpectedly, individual adults were more affected by the bite-block-plus-masking condition than were the children.

Variability

Tables 8.7 - 8.9 and 8.31 illustrate the overall summary statements made here. For the group, F2 and F1 variability were not significantly affected. The bite-block and bite-block-plus-masking conditions generally increased variability of F2 while masking decreased variability of F2, making them significantly different from each other, but not from the normal condition. However, half of the individual children exhibited a main effect of bite block on F2 collapsed across vowels. Comparing subject groups, it was unexpected to obtain a group finding of increased variability for /ae/ F2 in the bite-block condition for the adults, but none for the children.

A significant main effect of vowel on F1 standard deviation was found for half of the children: hat exhibited greatest F1 variability, hit less, and heat least. These findings were identical in the adults.

Discussion of and Conclusions Drawn from These Results

It may be concluded from these results that young children are less skilled in compensating for a bite block than are adults. The formant changes in bite-block conditions were larger than they were for the adults with normal hearing, but, as with the adults, the practical implications of these changes were not tested. It is not certain that the changes measured acoustically would affect vowel category assignment by listeners, but the possibility would be greater for the children than for the adults.

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It may also be concluded that auditory feedback does not play a role in the children's articulatory compensation. Listening to masking noise, either in isolation or while speaking with a bite block, did not systematically change target formant values. Overall variability in production was evident, as is often reported for children's utterances, such that effects of the independent variable may have been undetectable.

The theoretical implication of these findings is that articulatory compensation is a learned skill that develops over time in very young children. Children may require practice in listening to the auditory consequences of speech movement before they are able to use auditory feedback to guide articulation. Therefore, the hypotheses that four-year-old children with normal hearing perform adult-like compensation for a bite block and that auditory feedback plays a role in that compensation are rejected.

Given the findings that auditory feedback is used by adults with normal hearing to aid compensation for a bite block, but that children have not had enough practice at age four to use audition to guide articulation, one might not expect to see compensation in the adults with profound hearing loss, whose data will be presented next, given their limited or nonexistent opportunities to associate auditory feedback with articulation. In fact, the evidence showed the contrary.

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CHAPTER NINE

RESULTS: ADULTS WITH PROFOUND HEARING LOSS

The application of this experiment to a group of six adults with profound hearing loss tested the third hypothesis of this dissertation: Adults with profound hearing loss compensate for a bite block, as seen in adults with normal hearing, with or without auditory feedback.

Acoustic Analysis of Vowels Produced in Four Conditions: Measures of Articulatory Compensation

Group Data

Results were first examined using data averaged across the group of six subjects. The absolute formant frequency values used for statistical tests were recorded in Table 9.1a-c which follows. For figure presentations, percent change in formant frequency from normal to test conditions was used to illustrate changes in each of the second and first formants.

Direction of Change

The second formant measurements were averaged across the adults with profound hearing loss and examined for overall differences among conditions. The bar graphs on the left side of Figure 9.1 revealed that they showed small changes in F2 in test conditions compared to the normal condition, but in both directions. Computer simulation predicted that a bite block would result in a lowering of F2 from the normal condition. For the adults with profound hearing loss, F2 was raised for /I/ and minimally lowered in /i/ and /ae/. They displayed a modestly raised F2 across all vowels in the masking condition. The masking condition changes mirrored the direction of bite-block changes in hit only. The

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Table 9.1a.--Group Means, % Change, and Standard Deviations of F2 and F1 of "Heat" for Adults with Profound Hearing Loss

Sub-ject	Sex	Condition	Vowel	Mean F2	%Ch in F2	Mean F1	%Ch in F1	F2 SD	F1 SD
P1M	Male	Normal	heat	1678.56	***	332.69	***	53.22	26.24
P2F	Female	Normal	heat	1606.38	***	388.50	***	130.46	61.85
P3M	Male	Normal	heat	1536.30	***	341.10	***	112.38	16.81
P4M	Male	Normal	heat	1890.86	***	299.29	***	57.72	24.89
P5F	Female	Normal	heat	2404.25	***	339.38	***	95.76	20.47
P6M	Male	Normal	heat	2618.87	***	332.38	***	300.64	21.89
Group Means Per Condition				1955.87	***	338.89	***	125.03	28.69
P1M	Male	Bite-Block	heat	1608.75	-4.16	327.42	-1.58	83.04	42.28
P2F	Female	Bite-Block	heat	1569.47	-2.30	490.59	26.28	121.63	93.44
P3M	Male	Bite-Block	heat	1677.71	9.20	361.29	5.92	68.33	29.92
P4M	Male	Bite-Block	heat	1972.57	4.32	260.71	-12.89	64.86	28.79
P5F	Female	Bite-Block	heat	2446.11	1.74	346.22	2.02	97.96	13.11
P6M	Male	Bite-Block	heat	2299.07	-12.21	332.53	0.05	182.17	38.88
Group Means Per Condition				1928.95	-0.57	353.13	3.30	103.00	41.07
P1M	Male	Bite-Bl&Mskng	heat	1622.27	-3.35	344.00	3.40	91.32	46.29
P2F	Female	Bite-Bl&Mskng	heat	1717.81	6.94	453.50	16.73	98.89	84.52
P3M	Male	Bite-Bl&Mskng	heat	1795.60	16.88	347.60	1.91	72.79	40.23
P4M	Male	Bite-Bl&Mskng	heat	2044.00	8.10	308.73	3.15	76.85	11.67
P5F	Female	Bite-Bl&Mskng	heat	2426.62	0.93	372.92	9.88	152.80	21.56
P6M	Male	Bite-Bl&Mskng	heat	2232.80	-14.74	351.53	5.76	115.85	27.82
Group Means Per Condition				1973.18	2.46	363.05	6.81	101.42	38.68
P1M	Male	Masking	heat	1882.09	12.13	316.82	-4.77	83.48	29.55
P2F	Female	Masking	heat	1677.69	4.44	386.50	-0.51	88.68	54.00
P3M	Male	Masking	heat	1669.09	8.64	365.82	7.25	95.32	27.37
P4M	Male	Masking	heat	1817.00	-3.91	318.36	6.37	58.05	22.87
P5F	Female	Masking	heat	2372.00	-1.34	357.08	5.22	130.45	8.07
P6M	Male	Masking	heat	2501.56	-4.48	344.94	3.78	86.24	29.71
Group Means Per Condition				1986.57	2.58	348.25	2.89	90.37	28.60

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Table 9.1b.--Group Means, % Change, and Standard Deviations of F2 and F1 of "Hit" for Adults with Profound Hearing Loss

Sub-ject	Sex	Condition	Vowel	Mean F2	%Ch in F2	Mean F1	%Ch in F1	F2 SD	F1 SD
P1M	Male	Normal	hit	1678.50	***	429.81	***	72.68	25.29
P2F	Female	Normal	hit	1549.94	***	421.06	***	110.06	45.19
P3M	Male	Normal	hit	1441.64	***	438.79	***	64.16	48.40
P4M	Male	Normal	hit	1811.56	***	331.63	***	52.23	59.09
P5F	Female	Normal	hit	2375.92	***	343.25	***	102.10	22.55
P6M	Male	Normal	hit	1486.07	***	445.43	***	31.57	16.52
Group Means Per Condition				1723.94	***	401.66	***	72.13	36.17
P1M	Male	Bite-Block	hit	1636.14	-2.52	325.36	-24.30	82.54	33.84
P2F	Female	Bite-Block	hit	1586.53	2.36	515.87	22.52	126.95	90.43
P3M	Male	Bite-Block	hit	1586.60	10.06	411.70	-6.17	80.14	35.23
P4M	Male	Bite-Block	hit	1823.25	0.65	310.44	-6.39	97.79	100.21
P5F	Female	Bite-Block	hit	2469.21	3.93	353.00	2.84	90.85	17.45
P6M	Male	Bite-Block	hit	1528.25	2.84	490.25	10.06	57.57	21.35
Group Means Per Condition				1771.66	2.89	401.10	-0.24	89.31	49.75
P1M	Male	Bite-Bl&Mskng	hit	1603.83	-4.45	311.50	-27.53	74.43	36.54
P2F	Female	Bite-Bl&Mskng	hit	1611.87	4.00	503.40	19.56	195.65	140.17
P3M	Male	Bite-Bl&Mskng	hit	1691.93	17.36	428.87	-2.26	141.31	27.16
P4M	Male	Bite-Bl&Mskng	hit	1802.33	-0.51	357.27	7.73	88.32	72.14
P5F	Female	Bite-Bl&Mskng	hit	2363.11	-0.54	390.33	13.72	102.46	23.22
P6M	Male	Bite-Bl&Mskng	hit	1494.56	0.57	475.25	6.69	59.45	38.59
Group Means Per Condition				1761.27	2.74	411.10	2.99	110.27	56.30
P1M	Male	Masking	hit	1899.78	13.18	392.56	-8.67	90.82	27.00
P2F	Female	Masking	hit	1620.63	4.56	455.19	8.11	50.71	54.61
P3M	Male	Masking	hit	1573.70	9.16	391.00	-10.89	61.40	15.34
P4M	Male	Masking	hit	1779.53	-1.77	335.27	1.10	74.83	60.37
P5F	Female	Masking	hit	2282.92	-3.91	363.39	5.87	116.45	8.13
P6M	Male	Masking	hit	1499.56	0.91	421.81	-5.30	38.46	18.16
Group Means Per Condition				1776.02	3.69	393.20	-1.63	72.11	30.60

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Table 9.1c.--Group Means, % Change, and Standard Deviations of F2 and F1 of "Hat" for Adults with Profound Hearing Loss

Subject	Sex	Condition	Vowel	Mean F2	%Ch in F2	Mean F1	%Ch in F1	F2 SD	F1 SD
P1M	Male	Normal	hat	1526.19	***	359.75	***	72.49	48.45
P2F	Female	Normal	hat	1583.75	***	576.33	***	63.12	72.52
P3M	Male	Normal	hat	1380.00	***	618.30	***	29.65	21.54
P4M	Male	Normal	hat	1546.31	***	817.69	***	47.97	38.57
P5F	Female	Normal	hat	1741.20	***	1028.00	***	168.12	78.93
P6M	Male	Normal	hat	1337.81	***	658.94	***	40.17	28.88
Group Means Per Condition				1519.21	***	676.50	***	70.25	48.15
P1M	Male	Bite-Block	hat	1466.92	-3.88	405.92	12.83	43.45	45.46
P2F	Female	Bite-Block	hat	1576.21	-0.48	599.14	3.96	89.54	60.23
P3M	Male	Bite-Block	hat	1370.00	-0.72	530.40	-14.22	99.70	40.23
P4M	Male	Bite-Block	hat	1480.63	-4.25	760.38	-7.01	103.04	76.45
P5F	Female	Bite-Block	hat	1719.33	-1.26	895.80	-12.86	103.10	92.27
P6M	Male	Bite-Block	hat	1322.13	-1.17	697.50	5.85	58.11	34.79
Group Means Per Condition				1489.20	-1.96	648.19	-1.91	82.82	58.24
P1M	Male	Bite-Bl&Msknq	hat	1514.00	-0.80	441.25	22.65	145.09	51.55
P2F	Female	Bite-Bl&Msknq	hat	1686.50	6.49	549.36	-4.68	139.41	101.67
P3M	Male	Bite-Bl&Msknq	hat	1416.00	2.61	502.40	-18.74	121.30	56.96
P4M	Male	Bite-Bl&Msknq	hat	1498.64	-3.08	776.79	-5.00	65.92	63.70
P5F	Female	Bite-Bl&Msknq	hat	1619.38	-7.00	1022.56	-0.53	87.09	65.95
P6M	Male	Bite-Bl&Msknq	hat	1319.67	-1.36	700.33	6.28	36.40	38.25
Group Means Per Condition				1509.03	-0.52	665.45	0.00	99.20	63.01
P1M	Male	Masking	hat	1662.67	8.94	378.33	5.17	80.83	46.20
P2F	Female	Masking	hat	1596.85	0.83	594.54	3.16	76.21	55.54
P3M	Male	Masking	hat	1375.00	-0.36	617.40	-0.15	42.39	37.07
P4M	Male	Masking	hat	1573.19	1.74	768.75	-5.99	35.36	26.31
P5F	Female	Masking	hat	1756.71	0.89	1001.36	-2.59	60.13	63.58
P6M	Male	Masking	hat	1342.94	0.38	661.81	0.44	47.17	23.01
Group Means Per Condition				1551.23	2.07	670.37	0.01	57.02	41.95

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bite-block-plus-masking condition resulted in a raised F2 for the close vowels /i/ and /I/, but a lowered F2 for /ae/.

First formant measurements were next examined. The bar graphs on the right side of Figure 9.1 revealed that the profoundly hearing-impaired adults also displayed small changes in F1 in test conditions compared to the normal condition. Computer simulation predicted that a bite block would result in a raising of F1 from the normal condition. The adults with profound hearing loss exhibited a raised F1 in /i/, but a lowered F1 in the other two vowels. The masking condition (M) produced changes in F1 in the same direction as bite-block conditions for heat and hit, but resulted in no real change in hat.

Magnitude of Change

The left side of Figure 9.1 revealed that the adults with profound hearing loss exhibited very small changes in F2 in test conditions compared to the normal condition. Formant changes were on the order of 4% or less. To determine whether any of the observed differences were statistically significant, a one-way, repeated measures analysis of variance was performed on each vowel separately, as was done for all other subject groups. (See Table 9.2a.) No statistically significant differences were shown. Unlike the other subject groups, the adults with profound hearing loss had no missing data. Therefore, a two-way repeated measures analysis of variance (Vowel [3] by Condition [4]) was also performed. (See F table in Appendix E1a.) Only a significant effect of vowel on F2 was found, as would usually be expected, given the different characteristic F2 values accorded to vowels. However, of special note here is that it is well known that profoundly hearing-impaired talkers often neutralize vowels, diminishing contrasts among them. A significant effect of vowel indicates that these talkers were producing consistently distinct second formants for each of the three vowels in this study.

The right side of Figure 9.1 showed that, in terms of magnitude, test conditions produced very similar changes in F1, on the order of 7% or less. For the adults and the children with normal hearing, on the other hand, there was a greater contrast between the

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larger changes in F1 and the smaller changes in F2 for all vowels. Given the widely observed use of jaw movement (visible in speechreading) by deaf talkers to make distinctions among vowels, this finding is surprising. It was hypothesized that fixing the jaw would be quite disruptive to vowel production. A one-way, repeated measures ANOVA, as described previously, was performed on the profoundly hearing-impaired adults' individual mean F1 measurements for each vowel separately. (See Table 9.2b.) No statistically significant effects of condition were found. As with F2, a two-way, repeated measures ANOVA was also performed on F1. (See F Table in Appendix E1b.) Only a significant effect of vowel on F1 was found, as would be expected, given the different characteristic F1 values accorded to vowels. Again, as with F2, this finding indicates that these talkers were producing consistently distinct first formants for each of the three vowels in this study.

The mean standard deviation in Hertz of F2 and F1 was next examined (Figure 9.2). If one compares Figures 7.2, 8.2, and 9.2, it is apparent that F2 variability in the adults with profound hearing loss was greater than that seen in the adults with normal hearing, but less than that seen in the children. Variability in F1, however, was comparable across both adult groups, but larger in the children. To determine if there were significant differences among conditions in terms of variability of production, one-way, repeated measures ANOVAs, like those discussed previously, were performed for each vowel separately. (See Tables 9.2c and 9.2d.) The subjects showed no significant effects of condition on F2 standard deviation, but exhibited an effect of condition that approached significance on F1 standard deviation for /i/ ($p=.0591$) and /ae/ ($p=.0525$).

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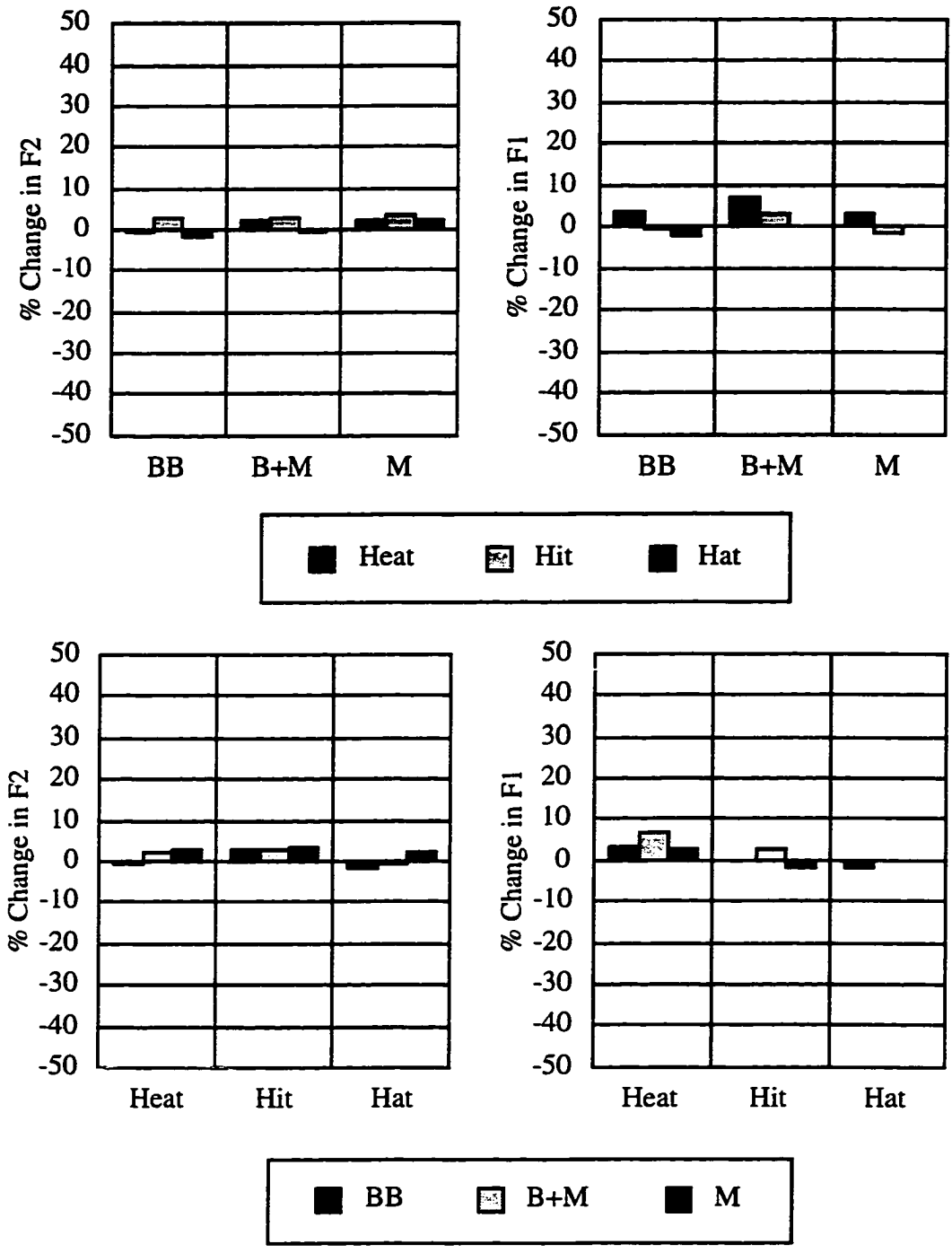


Fig. 9.1. Mean % Change from Normal Condition in F2 and F1 in Bite-Block (BB), Bite-Block-Plus-Masking (B+M), and Masking (M) Conditions for Adults with Profound Hearing Loss

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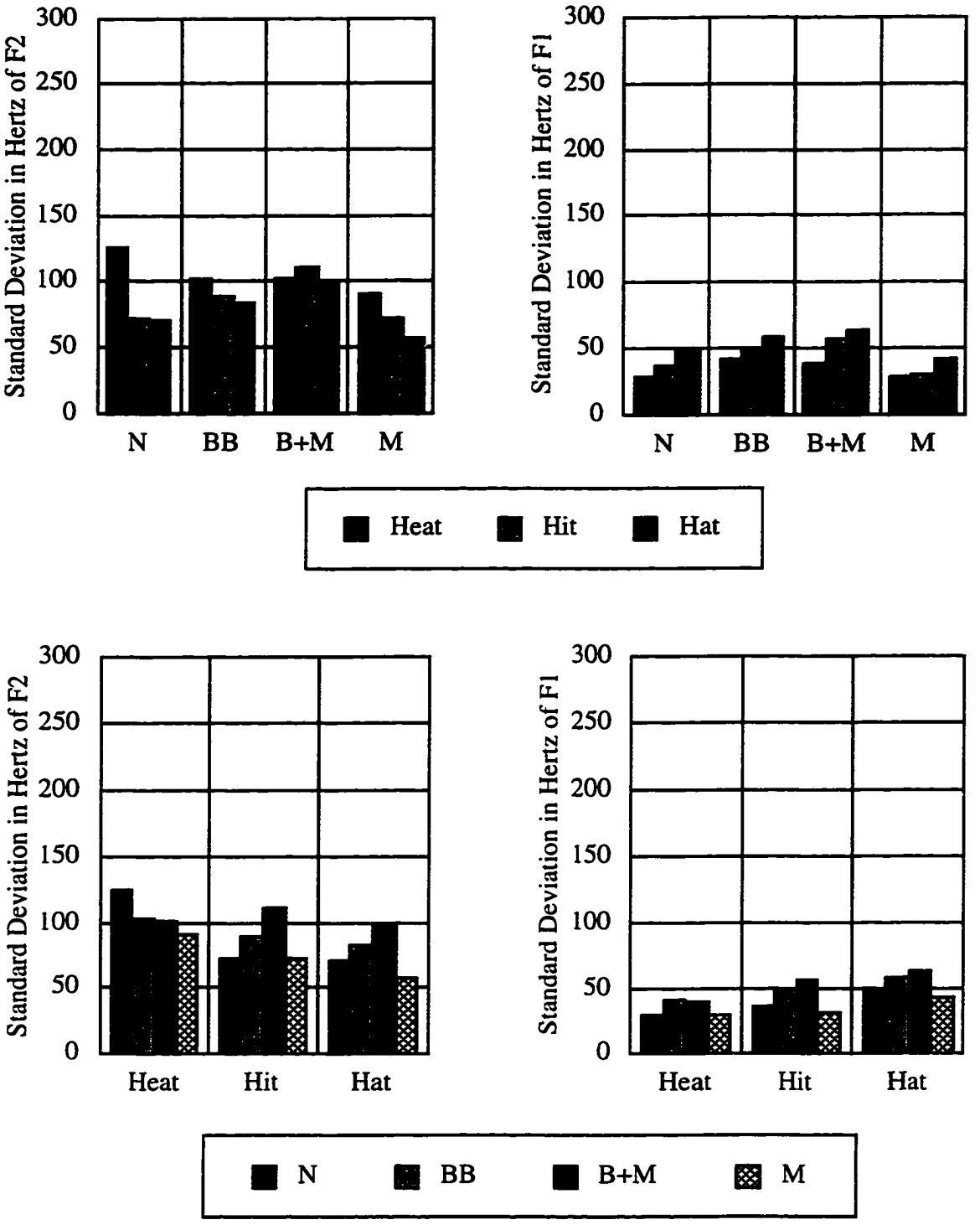


Fig. 9.2. Mean Standard Deviation in Hertz of F2 and F1 in Bite-Block (BB), Bite-Block-Plus-Masking (B+M), and Masking (M) Conditions for Adults with Profound Hearing Loss

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Table 9.2a.--Repeated Measures One-Way Analysis of Variance: Mean F2 for Group of Adults with Profound Hearing Loss

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Heat					
Condition	11136.00	3	3711.99	.26	.8511
Error	211908.70	15	14127.25		
Hit					
Condition	10092.65	3	3364.22	.52	.6770
Error	97632.94	15	6508.86		
Hat					
Condition	12074.31	3	4024.77	1.70	.2107
Error	35607.58	15	2373.84		

Table 9.2b.--Repeated Measures One-Way Analysis of Variance: Mean F1 for Group of Adults with Profound Hearing Loss

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Heat					
Condition	1822.35	3	607.45	.95	.4430
Error	9627.21	15	641.81		
Hit					
Condition	965.73	3	321.91	.23	.8715
Error	20664.48	15	1377.63		
Hat					
Condition	2662.71	3	887.57	.47	.7065
Error	28225.29	15	1881.69		

Table 9.2c.--Repeated Measures One-Way Analysis of Variance: Mean Standard Deviation of F2 for Group of Adults with Profound Hearing Loss

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Heat					
Condition	3792.46	3	1264.15	.65	.5942
Error	29102.85	15	1940.19		
Hit					
Condition	5910.78	3	1970.26	2.63	.0878
Error	11218.10	15	747.87		
Hat					
Condition	5827.95	3	1942.65	1.61	.2285
Error	18076.92	15	1205.13		

★★ = $p<.01$, ★ = $p<.05$

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Table 9.2d.--Repeated Measures One-Way Analysis of Variance: Mean Standard Deviation of F1 for Group of Adults with Profound Hearing Loss

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Heat					
Condition	774.15	3	258.05	3.09	.0591
Error	1253.14	15	83.54		
Hit					
Condition	2536.28	3	845.43	2.42	.1064
Error	5237.85	15	349.19		
Hat					
Condition	1639.24	3	546.41	3.23	.0525
Error	2538.71	15	169.25		

★★ = p<.01, ★ = p<.05

These near-significant findings were explored further with post hoc LSD comparisons of conditions (See Tables 9.3a and b.)

Table 9.3a.--Summary of Results of Post Hoc Tests of the Main Effect of Condition on Heat F1SD for Adults with Profound Hearing Loss

Mean /i/ F1SD in Four Conditions:			
N = 28.69	BB = 41.07	B+M = 38.68	M = 28.60
	N v. BB	p = .03316★	
	N v. B+M	p = .07780	
	N v. M	p = .98563	
	BB v. B+M	p = .65732	
	BB v. M	p = .03200★	
	B+M v. M	p = .07525	

Table 9.3b.--Summary of Results of Post Hoc Tests of the Main Effect of Condition on Hat F1SD for Adults with Profound Hearing Loss

Mean /ae/ F1SD in Four Conditions:			
N = 48.15	BB = 58.24	B+M = 63.01	M = 41.95
	N v. BB	p = .01130★	
	N v. B+M	p = .02806★	
	N v. M	p = .46649	
	BB v. B+M	p = .65537	
	BB v. M	p = .00245★★	
	B+M v. M	p = .00623★★	

★★ = p<.01, ★ = p<.05

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Comparing the post hoc findings and Figure 9.2, it appears that greater F1 variability resulted in the bite-block condition for /i/ and the bite-block and bite-block-plus-masking conditions for /ae/. A two-way repeated measures ANOVA, identical to that done for F2 and F1, was also performed for F2 and F1 standard deviations. (See Appendix E1c and d.) They yielded similar findings. A main effect of condition (p=.0095) was shown for F1 standard deviation. Post hoc LSD tests (See Appendix E2.) revealed that, collapsed across the three vowels, the bite-block and bite-block-plus-masking conditions resulted in greater F1 variability, compared to normal and masking conditions.

Summary

Tables 9.4 - 9.9 summarize the effects of all independent variables on all dependent variables for the group of adults with profound hearing loss and facilitate comparisons to the previous findings for the groups of adults and children with normal hearing. The reader is reminded that information from post hoc tests is provided only where a significant main effect of condition was obtained for a dependent variable.

The data from the group of adults with profound hearing loss revealed that:

A. the bite block condition lowered F2 in /i/ and /ae/, but raised F2 in /ɪ/. (See Table 9.4.) The changes were small and not significant. The results for this group contrast with those for the adults and the children with normal hearing, both of whom lowered F2 in every vowel, as predicted by computer simulation, with significant findings for /i/ in the adults and for all vowels in the children. The bite-block condition raised F1 in /i/, as predicted by computer simulation for both /i/ and /ɪ/, but lowered F1 in /ɪ/. The latter was not shown for the adults and the children with normal hearing. /ae/ F1 was lowered, as predicted for a less-than-normal-interincisal distance. These talkers might reasonably be expected to use typically large jaw excursions for open vowels, such that the 20-mm-bite-block condition presented a more-closed-than-normal posture, similar to the effect of the 10-mm bite block in the children. Like the adults with normal

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hearing, these subjects exhibited no significant changes in F1, but, surprisingly, the magnitude in percent change was smaller.

B. masking resulted in small, non-significant changes in F2 and F1 (See Table 9.5.) It is not unexpected that subjects with profound, congenital hearing loss were little affected by removal of their hearing aids and presentation of 80-dB masking. (Some subjects checked with the investigator to ask, "Is it on?") On the other hand, it is also extremely interesting to note that there was change, albeit small, and that the direction of that change was opposite that of the other two subject groups.

C. the bite-block-plus-masking condition resulted in small, non-significant changes to F2 and F1. (See Table 9.6.) Magnitude in percent-change in formants was less than for the adults or the children with normal hearing, and direction of change was also different for F2 in the close vowels. /i/ and /I/ F2 were raised rather than lowered, as they were in the other two subject groups.

D. test conditions did not result in significant changes in F2 variability, but the bite block increased the variability of F1 in heat and both the bite-block and the bite-block-plus-masking condition increased hat F1 variability. (Tables 9.7 - 9.9.) The other two subject groups showed no changes in F1 variability, but the adults with normal hearing had shown greater F2 variability for /ae/.

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Table 9.4.--Summary of Bite-Block Effects on F2 and F1 for Groups of Subjects

	Adults with Normal Hearing	**Children with Normal Hearing**	**Adults with Profound Hearing Loss**	Adults with Severe Hearing Loss
F2 Direction of Change:				
heat	lowered	lowered	lowered	
hit	lowered	lowered	raised	
hat	lowered	lowered	lowered	
% Change	<3%	<11%	<3%	
Post Hoc Tests of Main Effect of Condition for Heat:				
N v. BB	↓ ★	↓ ★★		
Hit:				
N v. BB		↓ ★		
Hat:				
N v. BB		↓ ★★		
F1 Direction of Change:				
heat	raised	raised	raised	
hit	raised	raised	lowered	
hat	raised	lowered	lowered	
% Change	<8%	<20%	<4%	
Post Hoc Tests of Main Effect of Condition for Heat:				
N v. BB				
Hit:				
N v. BB				
Hat:				
N v. BB		↓ ★★		

★★=p<.01, ★=p<.05, ↑ = raised formant, ↓ = lowered formant

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Table 9.5.--Summary of Masking Effects on F2 and F1 for Groups of Subjects

	Adults with Normal Hearing	**Children with Normal Hearing**	**Adults with Profound Hearing Loss**	Adults with Severe Hearing Loss
F2 Direction of Change:				
heat	lowered	lowered	raised	
hit	lowered	raised	raised	
hat	lowered	lowered	raised	
% Change	<4%	<2%	<4%	
Post Hoc Tests of Main Effect of Condition for Heat:				
N v. M	↓ ★			
BB v. M		★★		
Hit:				
N v. M				
BB v. M		★★		
Hat:				
N v. M				
BB v. M		★		
F1 Direction of Change:				
heat	raised	raised	raised	
hit	raised	raised	lowered	
hat	raised	raised	lowered	
% Change	<12%	<15%	<3%	
Post Hoc Tests of Main Effect of Condition for Heat:				
N v. M				
BB v. M				
Hit:				
N v. M				
BB v. M				
Hat:				
N v. M				
BB v. M		★★		

★★=p<.01, ★=p<.05, ↑ = raised formant, ↓ = lowered formant

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Table 9.6.--Summary of Bite-Block-Plus-Masking Effects on F2 and F1 for Groups of Subjects

	Adults with Normal Hearing	**Children with Normal Hearing**	**Adults with Profound Hearing Loss**	Adults with Severe Hearing Loss
F2 Direction of Change:				
heat	lowered	lowered	raised	
hit	lowered	lowered	raised	
hat	lowered	lowered	lowered	
% Change	<7%	<10%	<3%	
Post Hoc Tests of Main Effect of Condition for Heat:				
N v. BM	↓ ★★	↓ ★★		
BB v. B+M	★★			
M v. B+M	★★	★★		
Hit:				
N v. BM		↓ ★		
BB v. B+M				
M v. B+M		★★		
Hat:				
N v. BM	↓ ★★	↓ ★		
BB v. B+M				
M v. B+M				
F1 Direction of Change:				
heat	raised	raised	raised	
hit	raised	raised	raised	
hat	raised	lowered	unchanged	
% Change	<17%	<15%	<7%	
Post Hoc Tests of Main Effect of Condition for Heat:				
N v. BM				
BB v. B+M				
M v. B+M				
Hit:				
N v. BM	↑ ★★			
BB v. B+M	★★			
M v. B+M				
Hat:				
N v. BM		↓ ★		
BB v. B+M				
M v. B+M		★★		

★★=p<.01, ★=p<.05, ↑ = raised formant, ↓ = lowered formant

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Table 9.7.--Summary of Bite-Block Effects on F2SD and F1SD for Groups of Subjects

	Adults with Normal Hearing	**Children with Normal Hearing**	**Adults with Profound Hearing Loss**	Adults with Severe Hearing Loss
Post Hoc Tests of Main Effect of Condition for Heat F2SD: N v. BB				
Hit F2SD: N v. BB				
Hat F2SD: N v. BB	↑ ★★			
Post Hoc Tests of Main Effect of Condition for Heat F1SD: N v. BB			↑ ★[1]	
Hit F1SD: N v. BB				
Hat F1SD: N v. BB			↑ ★[2]	

★★=p<.01, ★=p<.05, ↑ = increased variability, ↓ = decreased variability

[1] Post hoc test conducted of a main effect of condition for heat F1 standard deviation of p=.0591.
[2] Post hoc test conducted of a main effect of condition for hat F1 standard deviation of p=.0525.

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Table 9.8.--Summary of Masking Effects on F2SD and F1SD for Groups of Subjects

	Adults with Normal Hearing	**Children with Normal Hearing**	**Adults with Profound Hearing Loss**	Adults with Severe Hearing Loss
Post Hoc Tests of Main Effect of Condition for Heat F2SD:				
N v. M				
BB v. M				
Hit F2SD:				
N v. M				
BB v. M				
Hat F2SD:				
N v. M				
BB v. M	★	★		
Post Hoc Tests of Main Effect of Condition for Heat F1SD:				
N v. M				
BB v. M				
Hit F1SD:				
N v. M				
BB v. M				
Hat F1SD:				
N v. M				
BB v. M			★★	

★★=p<.01, ★=p<.05, ↑ = increased variability, ↓ = decreased variability

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Table 9.9.--Summary of Bite-Block-Plus-Masking Effects on F2SD and F1SD for Groups of Subjects

	Adults with Normal Hearing	**Children with Normal Hearing**	**Adults with Profound Hearing Loss**	Adults with Severe Hearing Loss
Post Hoc Tests of Main Effect of Condition for Heat F2SD:				
N v. B+M				
BB v. B+M				
M v. B+M				
Hit F2SD:				
N v. B+M				
BB v. B+M				
M v. B+M				
Hat F2SD:				
N v. B+M				
BB v. B+M	★★			
M v. B+M		★		
Post Hoc Tests of Main Effect of Condition for Heat F1SD:				
N v. B+M				
BB v. B+M				
M v. B+M			★	
Hit F1SD:				
N v. B+M				
BB v. B+M				
M v. B+M				
Hat F1SD:				
N v. B+M			↑ ★[3]	
BB v. B+M				
M v. B+M			★★	

★★=p<.01, ★=p<.05, ↑ = increased variability, ↓ = decreased variability

[3] Post hoc test conducted of a main effect of condition for hat F1 standard deviation of p=.0525.

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Individual Data

To discover the distinctive patterns of compensatory adjustments made by individuals in response to test conditions, the data from each adult with profound hearing loss were analyzed separately. See Tables 9.10 - 9.15 and Figures 9.3 - 9.8b. A special note is required for subject P6M. Table 9.15 shows two sets of data for heat. P6M produced /i/ exhibiting a resonance in two spectral regions, each of which might be a possible second formant. The resonance in the 1400 to 1700 Hertz region may be a tracheal resonance. The subject's speech had a breathy quality. In that case, this resonance could be ignored and F2 could be designated as the resonance from approximately 1900 to 2500 Hertz. However, if this subject was "over-articulating" in an effort to make himself highly intelligible, he might have produced the /i/ articulation very far forward, which approaches a node in Fant's nomograms (Fant 1970, p.84) where F2 would be lowered, rather than raised, thus making the resonance in the lower region the true F2. With no means of resolving this issue, both sets of values are provided in Table 9.15 and are illustrated in Figures 9.8a and 9.8b. However, only the higher resonance yielded enough tokens in all conditions to make all statistical comparisons possible, so they were used to describe magnitude of change.

Direction of Change

F2

Computer simulation predicted that a bite block would lower F2. The adults with profound hearing loss exhibited this direction of change for hat only. /ae/ F2 was lowered for all six individuals in the bite-block condition. Five of the six talkers raised F2 in the bite-block condition of hit (all but P1M; Fig. 9.8 a). There was no clear direction of change for heat, in that F2 was raised in as many cases as it was lowered.

The masking condition (M) raised F2 in hit in four talkers (P1M, P2F, P3M, P6M). Hat F2 was raised for five of the individuals (all but P3M). There was no clear direction of

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change for heat, as F2 was raised in as many cases as it was lowered. The bite-block-plus-masking condition raised /i/ F2 for subjects P2F, P3M, P4M, and P5F, and lowered /ae/ F2 for subjects P1M, P4M, P5F, and P6M. There was no clear direction of change for /I/ F2 (raised for P2F, P3M, and P6M; lowered for P1M, P4M, P5F).

F1

The bite-block condition resulted in a raising of F1 for heat in a majority of the profoundly hearing-impaired adults (P2F, P3M, P5F and P6M), consistent with predictions from computer simulation. Direction of change for the other two vowels was unclear, because F1 was lowered in as many cases as it was raised.

Masking (M) raised F1 for heat in four subjects (P3M, P4M, P5F and P6M). No consistent direction of change was revealed for /I/ and /ae/, in that F1 was lowered as often as it was raised.

The bite-block-plus-masking condition raised F1 for /i/ in all the subjects and for /I/ in four of the talkers (P2F, P4M, P5F, and P6M). It lowered F1 for /ae/ in four individuals (P2F, P3M, P4M, and P5F).

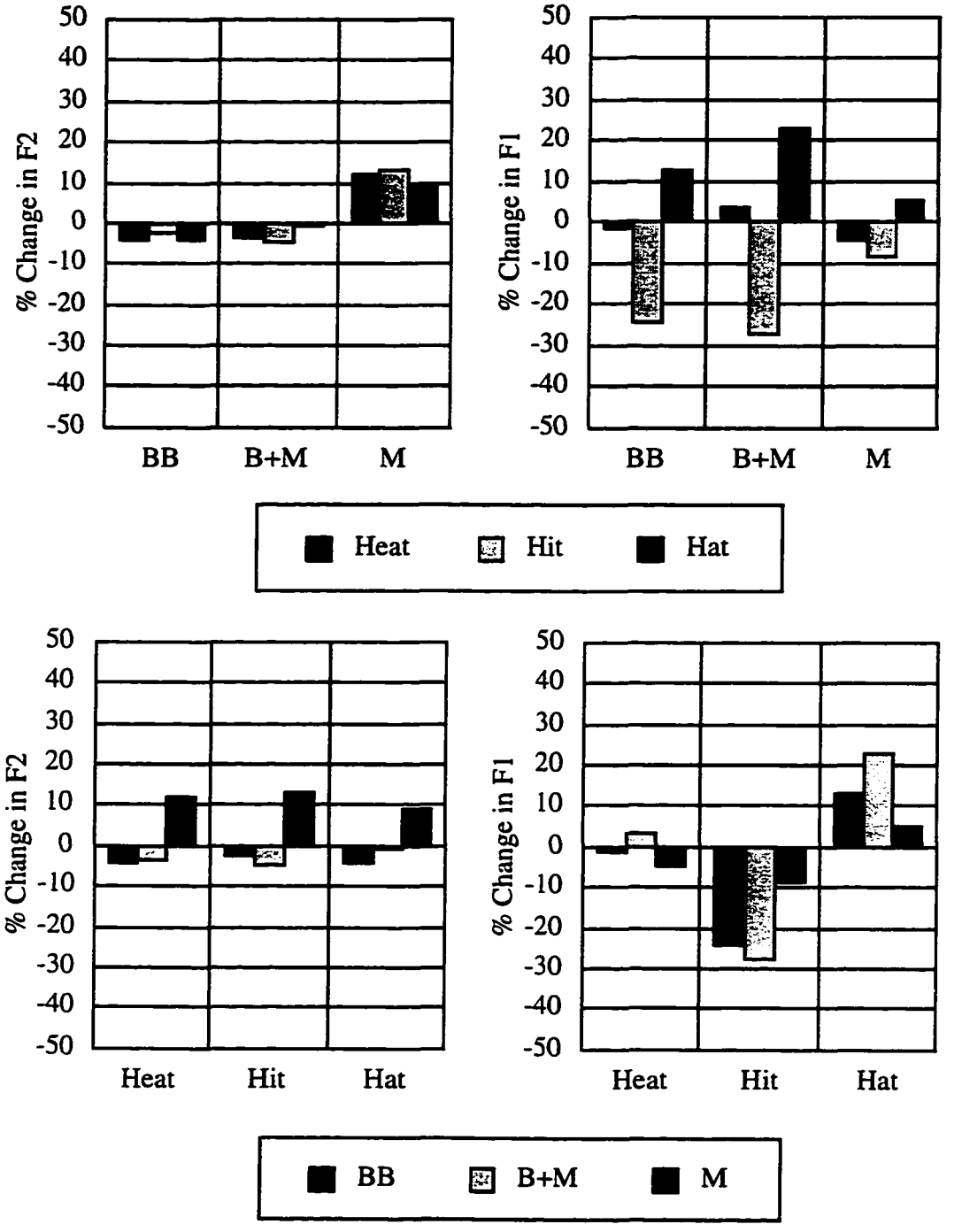
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Table 9.10.--Subject P1M: Means, Standard Deviations and Percent Change in Formants from Normal Condition to Test Conditions

Vowel	Condition	N	Mean F2	% Ch F2	Mean F1	% Ch F1	F2 St Dev	F1 St Dev
Heat	Normal	16	1678.56	***	332.69	***	53.22	26.24
	Bite Block	12	1608.75	-4.16	327.42	-1.58	83.04	42.28
	Bite Block and Masking	11	1622.27	-3.35	344.00	3.40	91.32	46.29
	Masking	11	1882.09	12.13	316.82	-4.77	83.48	29.55
Hit	Normal	16	1678.50	***	429.81	***	72.68	25.29
	Bite Block	14	1636.14	-2.52	325.36	-24.30	82.54	33.84
	Bite Block and Masking	12	1603.83	-4.45	311.50	-27.53	74.43	36.54
	Masking	9	1899.78	13.18	392.56	-8.67	90.82	27.00
Hat	Normal	16	1526.19	***	359.75	***	72.49	48.45
	Bite Block	13	1466.92	-3.88	405.92	12.83	43.45	45.46
	Bite Block and Masking	16	1514.00	-0.80	441.25	22.65	145.09	51.55
	Masking	15	1662.67	8.94	378.33	5.17	80.83	46.20

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Fig. 9.3. % Change from Normal Condition in F2 and F1 in Bite-Block (BB), Bite-Block-Plus-Masking (B+M), and Masking (M) Conditions for Subject P1M



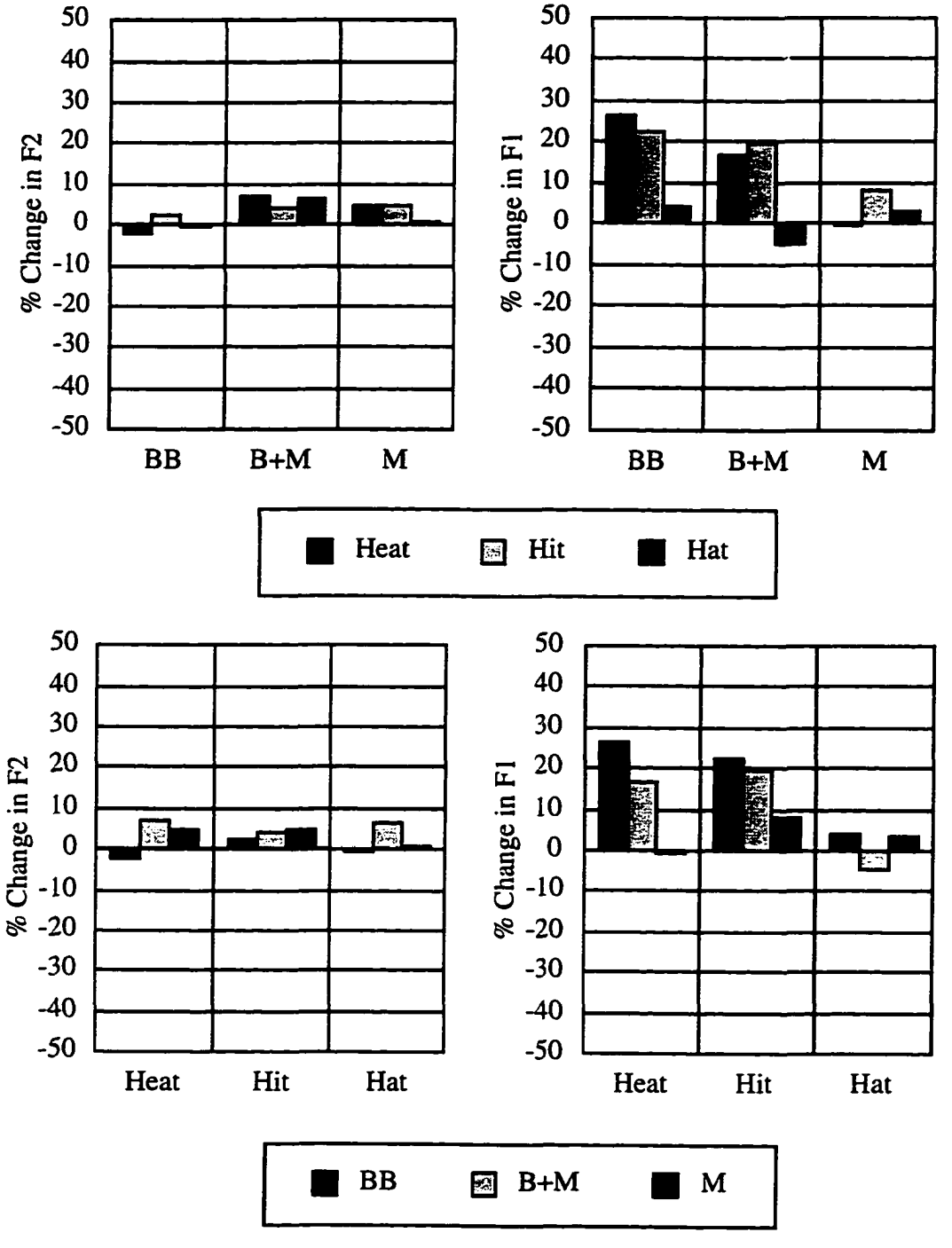
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Table 9.11.--Subject P2F: Means, Standard Deviations and Percent Change in Formants from Normal Condition to Test Conditions

Vowel	Condition	N	Mean F2	% Ch F2	Mean F1	% Ch F1	F2 St Dev	F1 St Dev
Heat	Normal	16	1606.38	***	388.50	***	130.46	61.85
	Bite Block	17	1569.47	-2.30	490.59	26.28	121.63	93.44
	Bite Block and Masking	16	1717.81	6.94	453.50	16.73	98.89	84.52
	Masking	16	1677.69	4.44	386.50	-0.51	88.68	54.00
Hit	Normal	16	1549.94	***	421.06	***	110.06	45.19
	Bite Block	15	1586.53	2.36	515.87	22.52	126.95	90.43
	Bite Block and Masking	15	1611.87	4.00	503.40	19.56	195.65	140.17
	Masking	16	1620.63	4.56	455.19	8.11	50.71	54.61
Hat	Normal	12	1583.75	***	576.33	***	63.12	72.52
	Bite Block	14	1576.21	-0.48	599.14	3.96	89.54	60.23
	Bite Block and Masking	14	1686.50	6.49	549.36	-4.68	139.41	101.67
	Masking	13	1596.85	0.83	594.54	3.16	76.21	55.54

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Fig. 9.4. % Change from Normal Condition in F2 and F1 in Bite-Block (BB), Bite-Block-Plus-Masking (B+M), and Masking (M) Conditions for Subject P2F



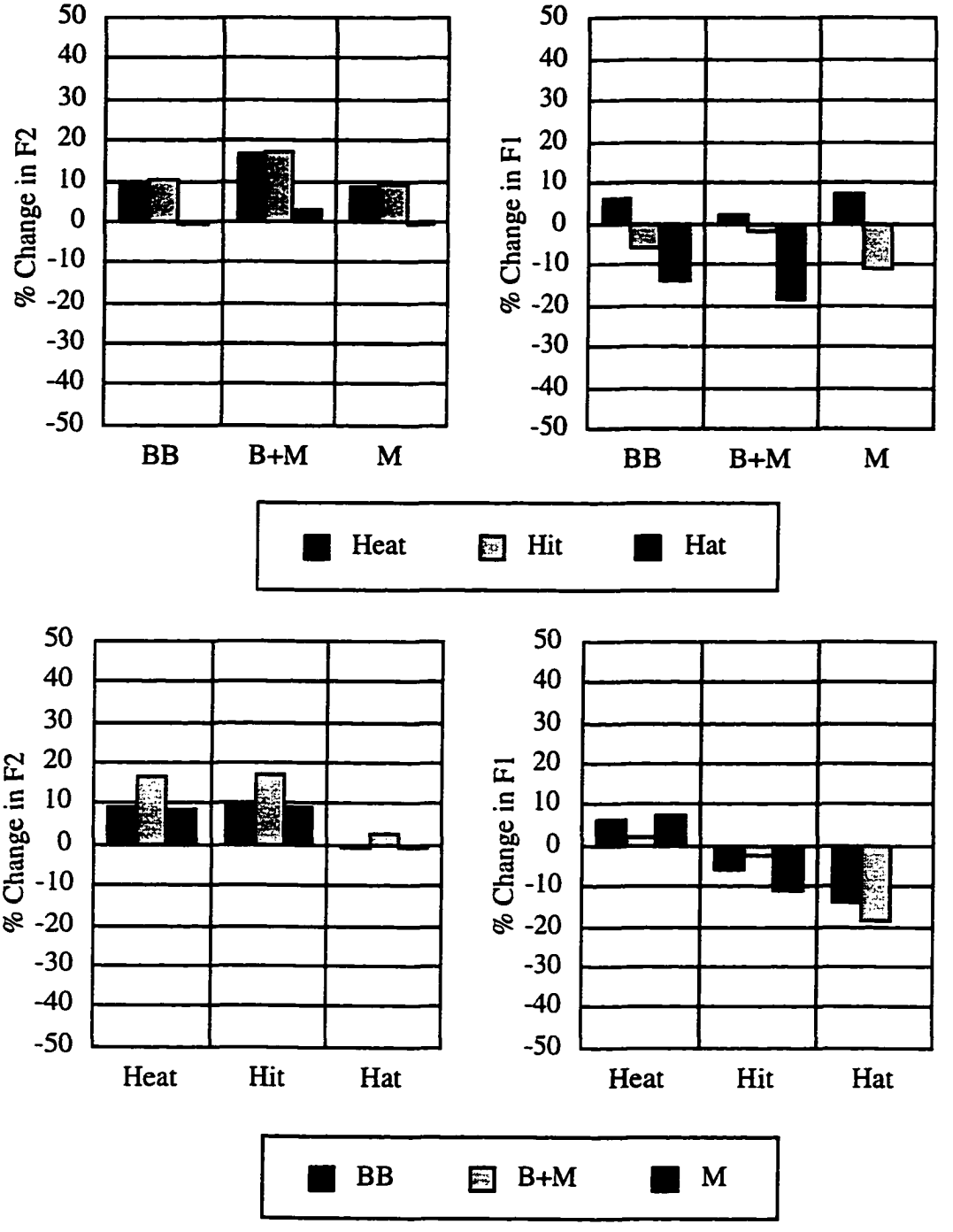
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Table 9.12.--Subject P3M: Means, Standard Deviations and Percent Change in Formants from Normal Condition to Test Conditions

Vowel	Condition	N	Mean F2	% Ch F2	Mean F1	% Ch F1	F2 St Dev	F1 St Dev
Heat	Normal	10	1536.30	***	341.10	***	112.38	16.81
	Bite Block	14	1677.71	9.20	361.29	5.92	68.33	29.92
	Bite Block and Masking	10	1795.60	16.88	347.60	1.91	72.79	40.23
	Masking	11	1669.09	8.64	365.82	7.25	95.32	27.37
Hit	Normal	14	1441.64	***	438.79	***	64.16	48.40
	Bite Block	10	1586.60	10.06	411.70	-6.17	80.14	35.23
	Bite Block and Masking	15	1691.93	17.36	428.87	-2.26	141.31	27.16
	Masking	10	1573.70	9.16	391.00	-10.89	61.40	15.34
Hat	Normal	16	1380.00	***	618.30	***	29.65	21.54
	Bite Block	13	1370.00	-0.72	530.40	-14.22	99.70	40.23
	Bite Block and Masking	16	1416.00	2.61	502.40	-18.74	121.30	56.96
	Masking	16	1375.00	-0.36	617.40	-0.15	42.39	37.07

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Fig. 9.5. % Change from Normal Condition in F2 and F1 in Bite-Block (BB), Bite-Block-Plus-Masking (B+M), and Masking (M) Conditions for Subject P3M



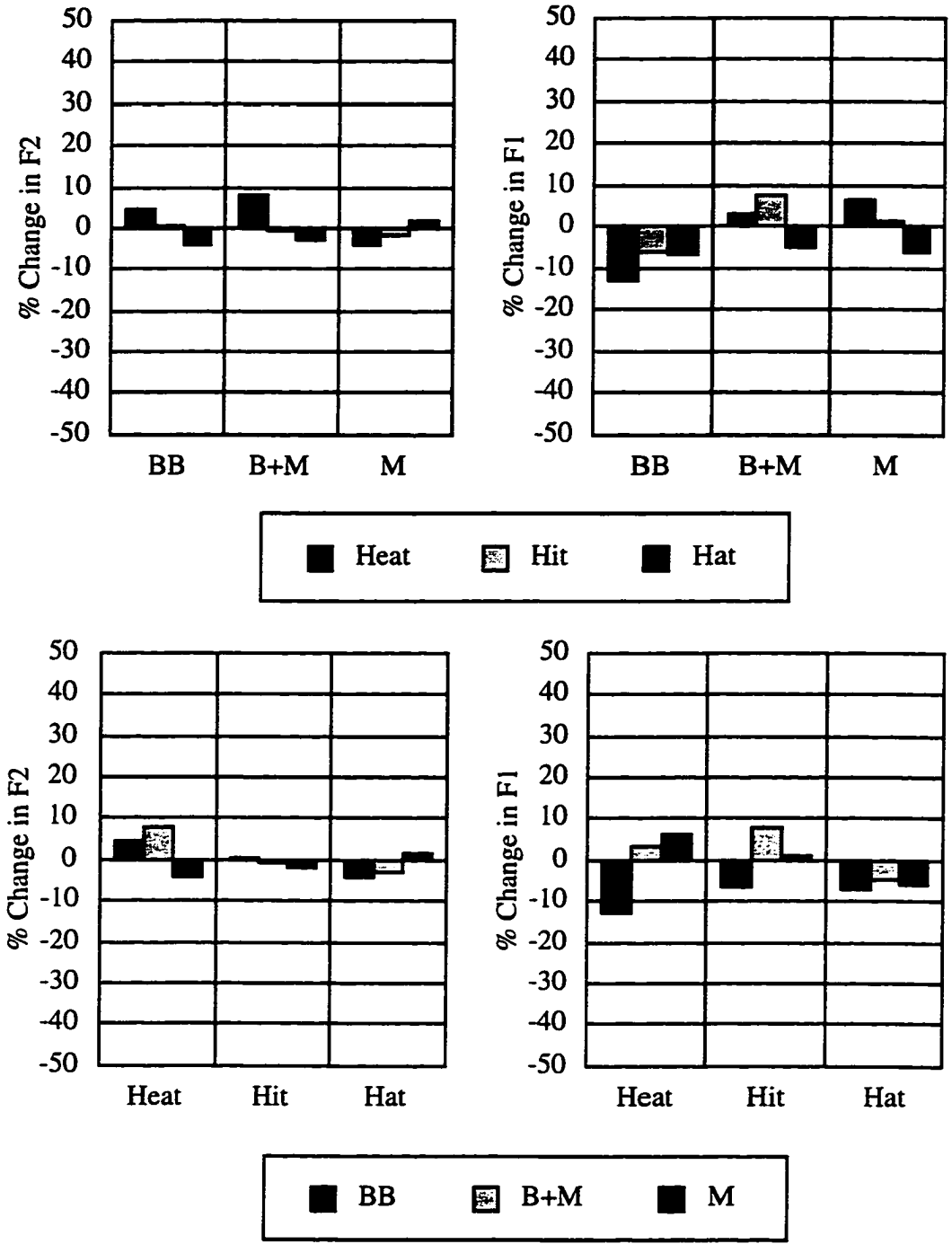
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Table 9.13.--Subject P4M: Means, Standard Deviations and Percent Change in Formants from Normal Condition to Test Conditions

Vowel	Condition	N	Mean F2	% Ch F2	Mean F1	% Ch F1	F2 St Dev	F1 St Dev
Heat	Normal	14	1890.86	***	299.29	***	57.72	24.89
	Bite Block	14	1972.57	4.32	260.71	-12.89	64.86	28.79
	Bite Block and Masking	11	2044.00	8.10	308.73	3.15	76.85	11.67
	Masking	11	1817.00	-3.91	318.36	6.37	58.05	22.87
Hit	Normal	16	1811.56	***	331.63	***	52.23	59.09
	Bite Block	16	1823.25	0.65	310.44	-6.39	97.79	100.21
	Bite Block and Masking	15	1802.33	-0.51	357.27	7.73	88.32	72.14
	Masking	15	1779.53	-1.77	335.27	1.10	74.83	60.37
Hat	Normal	16	1546.31	***	817.69	***	47.97	38.57
	Bite Block	16	1480.63	-4.25	760.38	-7.01	103.04	76.45
	Bite Block and Masking	14	1498.64	-3.08	776.79	-5.00	65.92	63.70
	Masking	16	1573.19	1.74	768.75	-5.99	35.36	26.31

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Fig. 9.6. % Change from Normal Condition in F2 and F1 in Bite-Block (BB), Bite-Block-Plus-Masking (B+M), and Masking (M) Conditions for Subject P4M



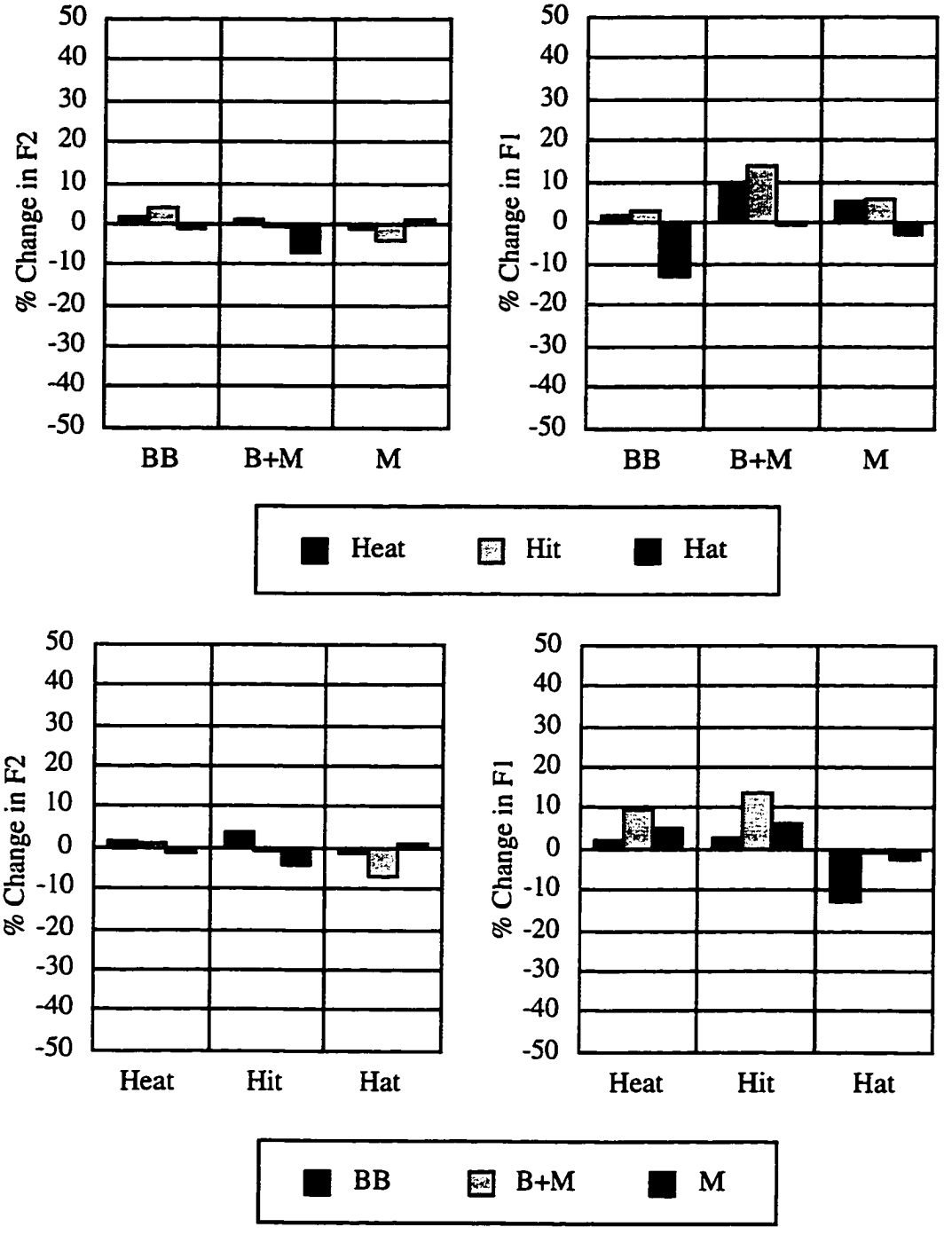
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Table 9.14.--Subject P5F: Means, Standard Deviations and Percent Change in Formants from Normal Condition to Test Conditions

Vowel	Condition	N	Mean F2	% Ch F2	Mean F1	% Ch F1	F2 St Dev	F1 St Dev
Heat	Normal	8	2404.25	***	339.38	***	95.76	20.47
	Bite Block	9	2446.11	1.74	346.22	2.02	97.96	13.11
	Bite Block and Masking	13	2426.62	0.93	372.92	9.88	152.80	21.56
	Masking	12	2372.00	-1.34	357.08	5.22	130.45	8.07
Hit	Normal	12	2375.92	***	343.25	***	102.10	22.55
	Bite Block	14	2469.21	3.93	353.00	2.84	90.85	17.45
	Bite Block and Masking	9	2363.11	-0.54	390.33	13.72	102.46	23.22
	Masking	13	2282.92	-3.91	363.39	5.87	116.45	8.13
Hat	Normal	15	1741.20	***	1028.00	***	168.12	78.93
	Bite Block	15	1719.33	-1.26	895.80	-12.86	103.10	92.27
	Bite Block and Masking	16	1619.38	-7.00	1022.56	-0.53	87.09	65.95
	Masking	14	1756.71	0.89	1001.36	-2.59	60.13	63.58

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Fig. 9.7. % Change from Normal Condition in F2 and F1 in Bite-Block (BB), Bite-Block-Plus-Masking (B+M), and Masking (M) Conditions for Subject P5F



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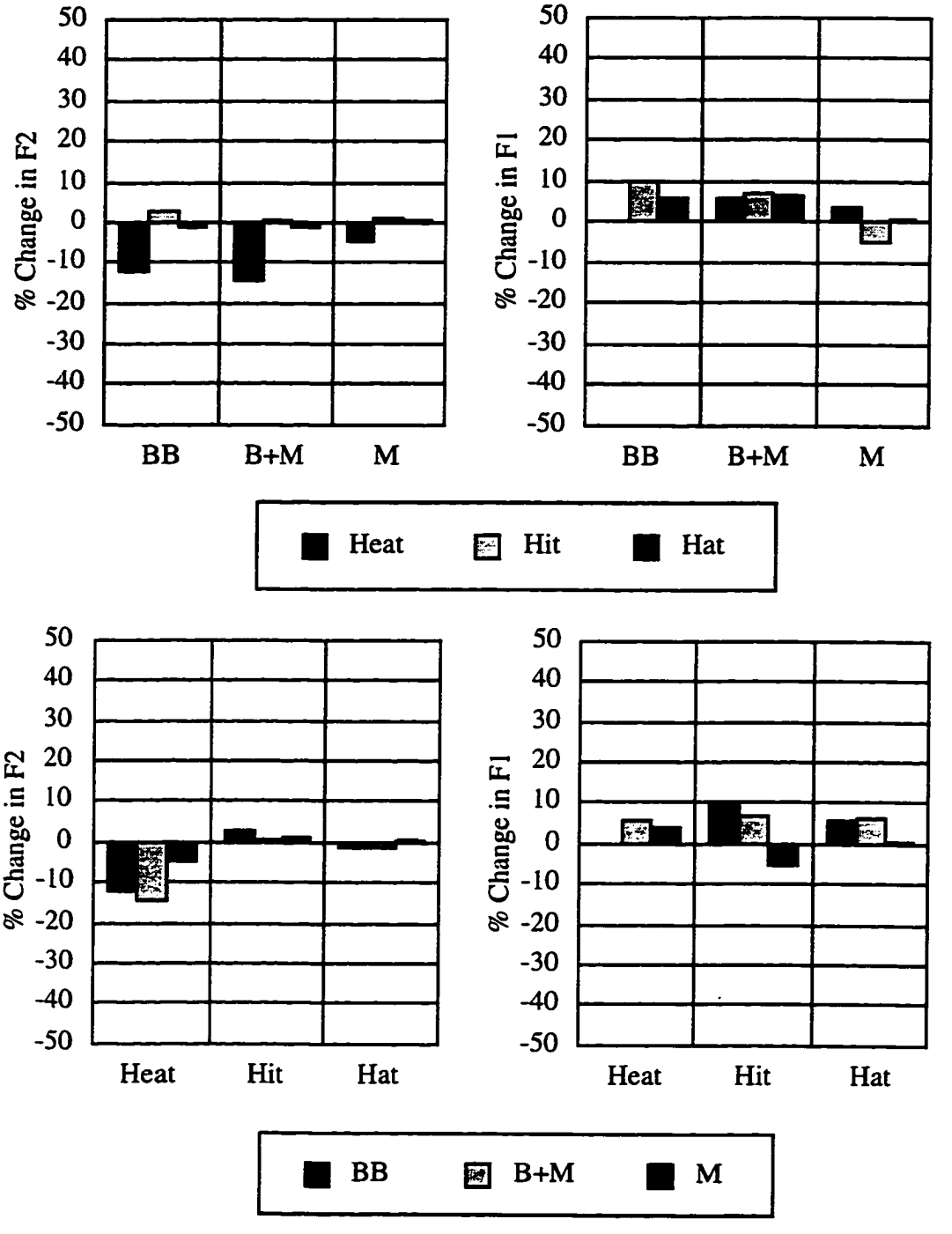
Table 9.15.--Subject P6M: Means, Standard Deviations and Percent Change in Formants from Normal Condition to Test Conditions

Vowel	Condition	N	Mean F2	% Ch F2	Mean F1	% Ch F1	F2 St Dev	F1 St Dev
Heat	Normal	15	2618.87	***	332.38	***	300.64	21.89
	Bite Block	15	2299.07	-12.21	332.53	0.05	182.17	38.88
	Bite Block and Masking	15	2232.80	-14.74	351.53	5.76	115.85	27.82
	Masking	16	2501.56	-4.48	344.94	3.78	86.24	29.71
Hit	Normal	14	1486.07	***	445.43	***	31.57	16.52
	Bite Block	16	1528.25	2.84	490.25	10.06	57.57	21.35
	Bite Block and Masking	16	1494.56	0.57	475.25	6.69	59.45	38.59
	Masking	16	1499.56	0.91	421.81	-5.30	38.46	18.16
Hat	Normal	16	1337.81	***	658.94	***	40.17	28.88
	Bite Block	16	1322.13	-1.17	697.50	5.85	58.11	34.79
	Bite Block and Masking	15	1319.67	-1.36	700.33	6.28	36.40	38.25
	Masking	16	1342.94	0.38	661.81	0.44	47.17	23.01
Heat[4]	Normal	16	1767.81	***	332.38	***	334.37	21.89
	Bite Block	13	1772.46	0.26	332.53	0.05	36.48	38.88
	Bite Block and Masking	15	1684.00	-4.74	351.53	5.76	46.14	27.82
	Masking	6	N/A	N/A	N/A	N/A	N/A	N/A

[4] See explanation in first paragraph of "Individual Data".

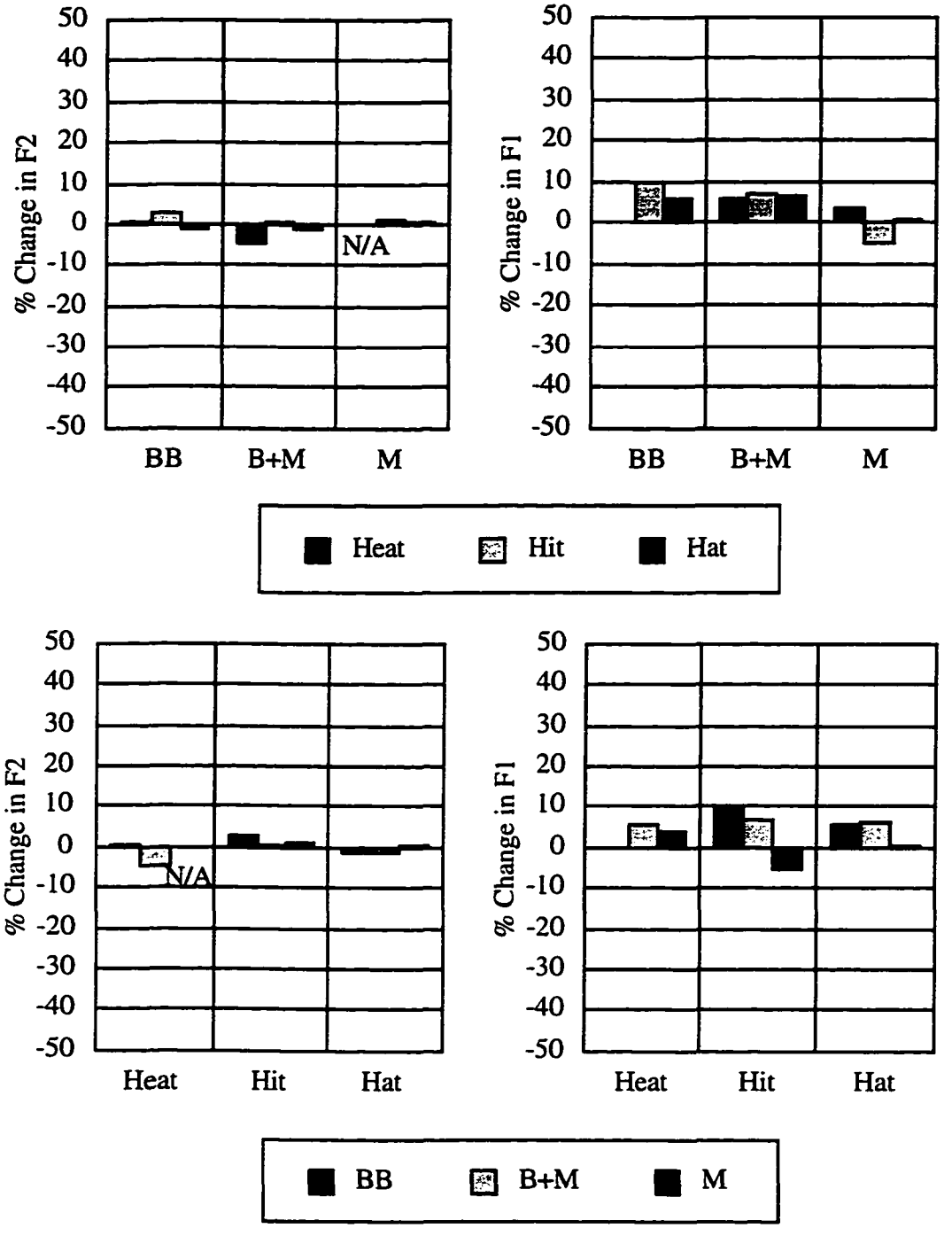
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Fig. 9.8a. % Change from Normal Condition in F2 and F1 in Bite-Block (BB), Bite-Block-Plus-Masking (B+M), and Masking (M) Conditions for Subject P6M



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Fig. 9.8b. % Change from Normal Condition in F2 and F1 in Bite-Block (BB), Bite-Block-Plus-Masking (B+M), and Masking (M) Conditions for Subject P6M



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Magnitude of Change

To determine whether observed changes were statistically significant, three-way ANOVAs were performed for F2 and F1 for each profoundly hearing-impaired adult separately, treating each token from each condition as one sample, just as had been done with individual adults and children with normal hearing. Two-way ANOVAs, also identical to those performed for individual adults and children with normal hearing, were performed on the standard deviation values of F2 and F1 for each subject separately, using the twelve standard deviation values from three vowels in four conditions as the raw data. Three-way ANOVAs could not be performed because each cell had only one value. Thus the analyses were collapsed across one dimension, to perform two-way ANOVAs (BB x M; BB x V; and M x V). All F tables for all the reported results that follow may be found for each adult with profound hearing loss (P1-P6) as Appendices E3-E8, respectively.

F2

Table 9.16 summarizes the statistically significant changes in F2 frequency and F2 variability found for each individual adult with profound hearing loss.

A majority (four of six) of the adults with profound hearing loss showed a significant main effect of bite block for F2. The effect was highly significant ($p<.01$) for each.

Surprisingly, a majority (five of six) of the adults with profound hearing loss exhibited a significant main effect of masking for F2. It will be remembered that these subjects removed their hearing aid(s) and listened to masking noise in this condition.

For this subject group it should be noted that there was a significant main effect of vowel on F2. While the speech of profoundly hearing-impaired individuals is often characterized by neutralized vowels in which formant regions overlap, these talkers made individually consistent F2 distinctions among the three vowels used in this study.

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Only two subjects with profound hearing loss showed a significant interaction of bite-block and masking effects on F2 collapsed across vowels. (See Table 9.16.) Subsequent Post Hoc Tukey HSD tests for unequal sample sizes (See Table 9.19.) revealed that subject P1M experienced significant F2 changes from normal in every test condition except the bite-block-plus-masking condition. The largest change was in the masking condition, where F2 was raised! The bite-block conditions lowered F2, so the masking condition was significantly different from every other condition. (See Figure 9.3.) The only significant difference found for Subject P4M was between the masking condition which lowered F2 and the bite-block-plus-masking condition which raised F2 (collapsed across vowels) from the normal condition. (See Figure 9.6.)

The bite block resulted in greater F2 variability for P3M and P4M, who exhibited a significant main effect of bite block. (See Table 9.16.)

P6M showed a main effect of vowel on F2 variability. (See Table 9.16.) Post Hoc Tukey HSD tests of differences between the standard deviations of F2 of each vowel, collapsed across all conditions, revealed that heat F2SD (171.23) was significantly greater than hit F2SD (46.76), $p = .0077$, or hat F2SD (45.46), $p = .0073$.

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Table 9.16.--Summary of Significant Changes in F2 and F2 Standard Deviation for Individual Adults with Profound Hearing Loss

Significant Changes in F2						
	P1M	P2F	P3M	P4M	P5F	P6M
Main Effect of Bite Block	↓ ★★		↑ ★★	↑ ★★		↓ ★★
Main Effect of Masking	↑ ★★	↑ ★★	↑ ★★		↓ ★★	↓ ★
Main Effect of Vowel	★★	★	★★	★★	★★	★★
Interaction of Bite Block and Masking	★★			★		
Significant Changes in F2 Standard Deviation						
	P1M	P2F	P3M	P4M	P5F	P6M
Main Effect of Bite Block			★	★		
Main Effect of Masking						
Main Effect of Vowel						★★
Interaction of Bite Block and Masking						

★★=p<.01, ★=p<.05; ↑ = raised formant, ↓ = lowered formant

F1

Table 9.17 displays, in summary, the statistically significant changes in F1 frequency and F1 variability found for each individual adult with profound hearing loss. A significant (p<.01) main effect of bite block for F1 was exhibited by half of the subjects. Only subject P5F exhibited a main effect (p<.01) of masking. (See Table 9.17.)

For this subject group it should again be noted that there was a significant main effect of vowel on F1 for every individual. (See Table 9.17.) As stated above, the speech of profoundly hearing-impaired individuals is often characterized by neutralized vowels in

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which formant regions overlap, but these talkers made individually consistent F1 distinctions among the three vowels used in this study.

Half of the profoundly hearing-impaired talkers showed a significant interaction of bite-block and masking effects on F1. (See Table 9.17.) Table 9.19 displays a summary of Post Hoc Tukey HSD tests for unequal sample sizes of the interaction of bite-block and masking effects on F1 for P2F, P4M and P5F. (Both female subjects displayed significant interactions of bite block and masking.) The women, P2F and P5F, exhibited a raised F1 for heat and hit in the bite-block and bite-block-plus-masking conditions, but the male subject, P4M, lowered F1, in the bite-block condition. (Refer to Figures 9.4, 9.6, and 9.7.) The women also exhibited significant differences between masking and bite-block conditions, the latter causing more change from normal condition than the former. (See Table 9.19.) These individual profiles may suggest that the women were more affected by the bite block in production of the high vowels than were the men, though there are not enough subjects to be sure of that.

A majority of the profoundly hearing-impaired talkers showed a significant main effect of bite block on F1 standard deviation. (See Table 9.17.) They exhibited greater overall variability in bite-block conditions. Half of the profoundly hearing-impaired speakers showed a main effect of vowel on F1 variability. (See Table 9.17.) Subsequent Post Hoc Tukey HSD tests revealed the following trend: F1 was most variable in hat, less so in hit, and least in heat, collapsed across condition. (See Table 9.18.)

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Table 9.17.--Summary of Significant Changes in F1 and F1 Standard Deviation for Individual Adults with Profound Hearing Loss

Significant Changes in F1						
	P1M	P2F	P3M	P4M	P5F	P6M
Main Effect of Bite Block		↑ ★★	↓ ★★			↑ ★★
Main Effect of Masking					↑ ★★	
Main Effect of Vowel	★★	★★	★★	★★	★★	★★
Interaction of Bite Block and Masking		★		★★	★★	
Significant Changes in F1 Standard Deviation						
	P1M	P2F	P3M	P4M	P5F	P6M
Main Effect of Bite Block	★★	★★[5]		★		★
Main Effect of Masking						
Main Effect of Vowel	★★			★★[6]	★★	
Interaction of Bite Block and Masking						

★★=p<.01, ★=p<.05; ↑ = raised formant, ↓ = lowered formant

[5]The main effect of bite block reached the p<.01 significance level in the bite-block x masking two-way ANOVA, but reached the p<.05 level of significance in the bite-block x vowel two-way ANOVA.
[6]The main effect of vowel reached the p<.01 significance level in the bite-block x vowel two-way ANOVA, but reached the p<.05 level of significance in the masking x vowel two-way ANOVA.

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Table 9.18.--Summary of Results of Post Hoc Tests of the Main Effect of Vowel for F1 Standard Deviation for Individual Adults with Profound Hearing Loss

P1M	Standard Deviation of F1		
	Heat 36.09	Hit 30.67	Hat 47.92
Heat v. Hat	p = .0017★★	Bite Block x Vowel Two-Way ANOVA	
Hit v. Hat	p = .0004★★	Bite Block x Vowel Two-Way ANOVA	
P4M	**Standard Deviation of F1**		
	Heat 22.06	Hit 72.95	Hat 51.26
Heat v. Hit	p = .0015★★	Bite Block x Vowel Two-Way ANOVA	
Heat v. Hit	p = .0266★	Masking x Vowel Two-Way ANOVA	
Heat v. Hat	p = .0205★	Bite Block x Vowel Two-Way ANOVA	
P5F	**Standard Deviation of F1**		
	Heat 15.80	Hit 17.84	Hat 75.18
Heat v. Hat	p = .0008★★	Bite Block x Vowel Two-Way ANOVA	
Heat v. Hat	p = .0003★★	Masking x Vowel Two-Way ANOVA	
Hit v. Hat	p = .0009★★	Bite Block x Vowel Two-Way ANOVA	
Hit v. Hat	p = .0003★★	Masking x Vowel Two-Way ANOVA	

★★ = $p<.01$, ★ = $p<.05$

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Table 9.19.--Summary of Post Hoc Tests of Significant Interactions of Bite-Block and Masking Effects (Collapsed Across Vowels) on F2 and F1 for Individual Adults with Profound Hearing Loss

Significant Differences in F2						
Condition	P1M	P2F	P3M	P4M	P5F	P6M
Normal vs. Bite Block	↓ ★					
Normal vs. Bite Block and Masking						
Normal vs. Masking	↑ ★★					
Masking vs. Bite Block	★★					
Masking vs. Bite Block and Masking	★★			★★		
Bite Block vs. Bite Block and Masking						
Significant Differences in F1						
Condition	P1M	P2F	P3M	P4M	P5F	P6M
Normal vs. Bite Block		↑ ★★		↓ ★★	↓ ★★	
Normal vs. Bite Block and Masking						
Normal vs. Masking						
Masking vs. Bite Block		★★			★★	
Masking vs. Bite Block and Masking						
Bite Block vs. Bite Block and Masking				★	★★	

★★=p<.01, ★=p<.05; ↑ = raised formant, ↓ = lowered formant

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Change Relative to Vowel Target

In the previous section, "Magnitude of Change," discussion was given to the results of ANOVAs that examined the effect of test conditions collapsed across vowels. Those same ANOVAs also revealed some condition-by-vowel interactions that will be taken up here. It will be seen, both in figures and tests of significance, that some conditions affected some vowels more than others.

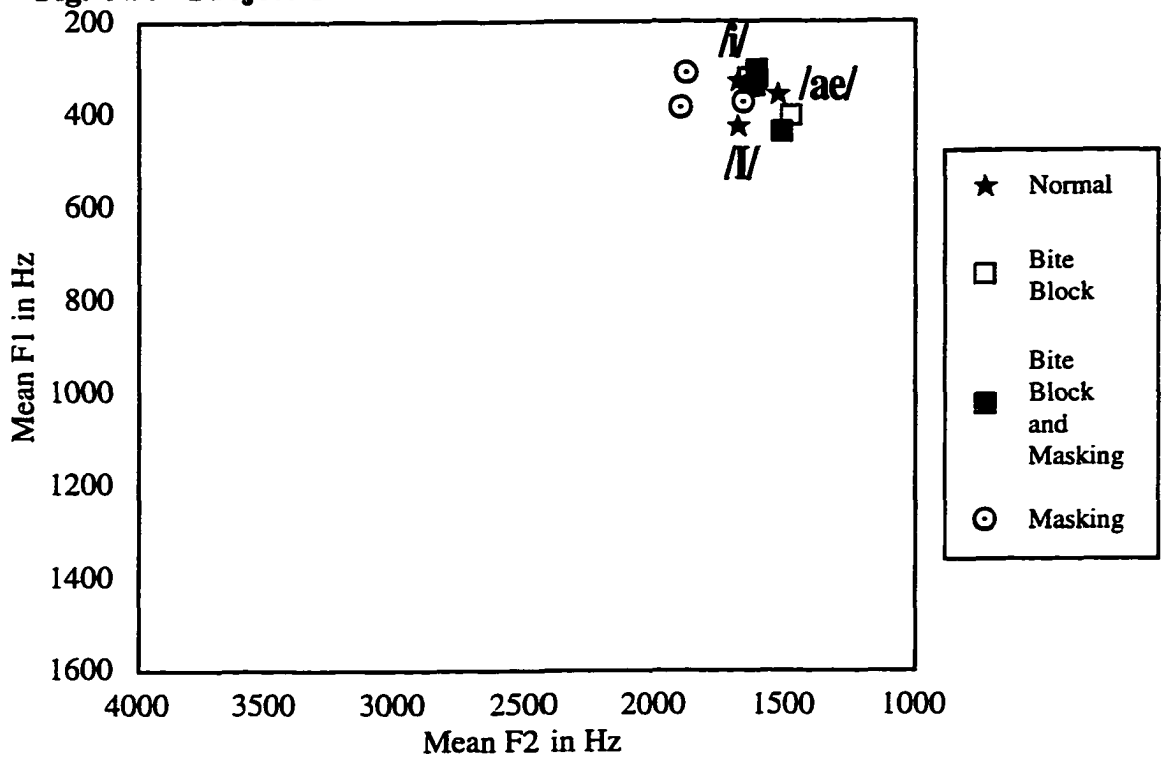
First, these effects have been presented graphically for each subject. Figures 9.9 - 9.20b follow. Two figures, identical to those that were displayed for each adult and child with normal hearing are presented per page for each of the adults with profound hearing loss. The figure at the top of the page displays mean F2 and F1 values from each condition in a traditional F1-by-F2 plot of "vowel space." The figures at the bottom of each page present two panels, left and right, of plots of the standard deviation of F2 and F1, respectively. The figures display the effects of test condition, depending on vowel target, on both mean formant measures and the variability of production. They also reveal the profiles of articulatory adjustments by each individual.

While the figures illustrate individual differences in the effect of test conditions and articulatory adjustments, one must return to the statistical tests of significance in order to make useful generalizations about conditions that changed the production of some vowels more than others.

Summary tables are presented below to consolidate the detailed results. All F tables for all of the following reported results may be found for each adult with profound hearing loss (P1-P6) as Appendices E3 - E8, respectively.

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Fig. 9.9. Subject P1M: Mean F1 x F2 Plot of Vowels in Each Condition



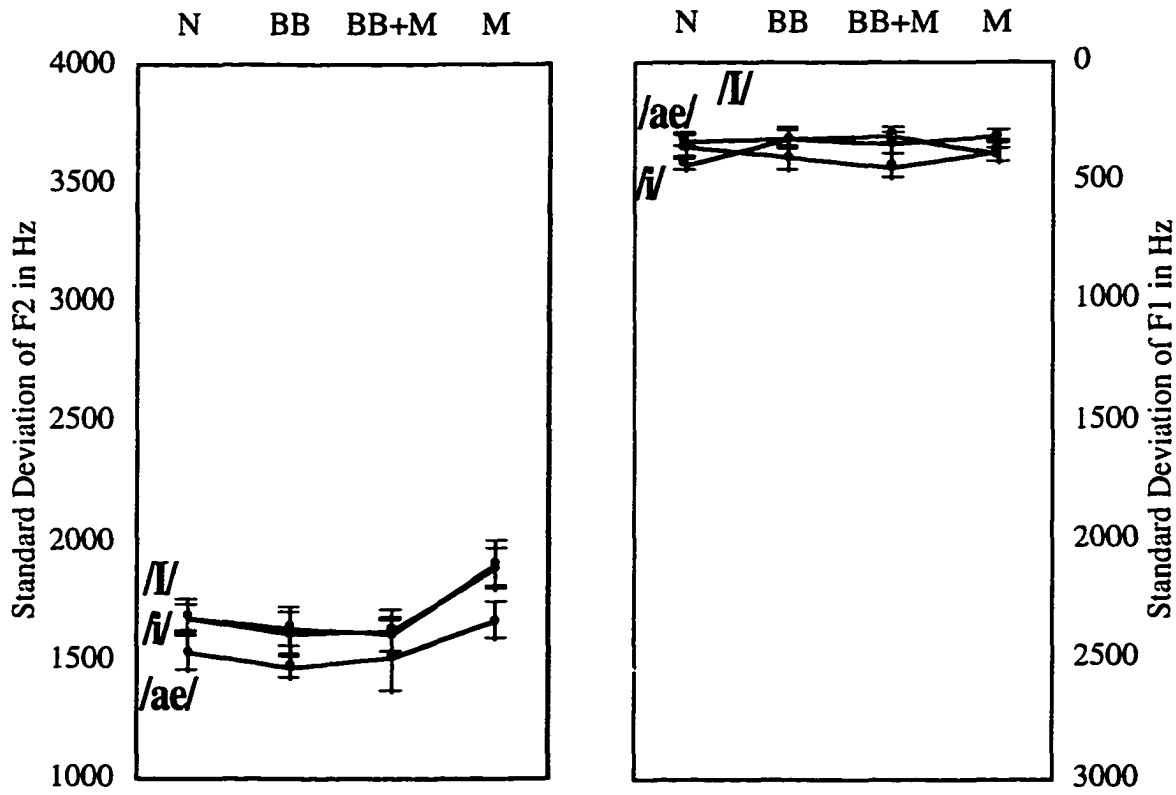
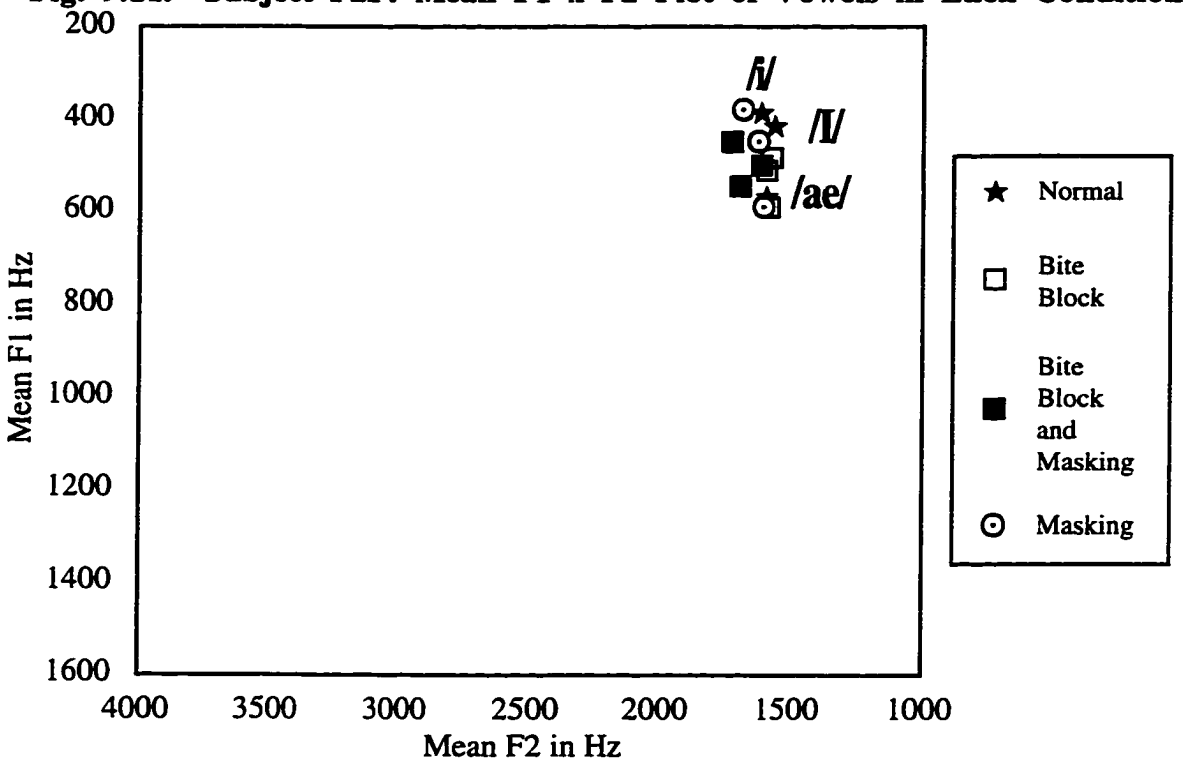


Fig. 9.10. P1M: Plots of One SD Above and Below Mean F2 and F1

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Fig. 9.11. Subject P2F: Mean F1 x F2 Plot of Vowels in Each Condition



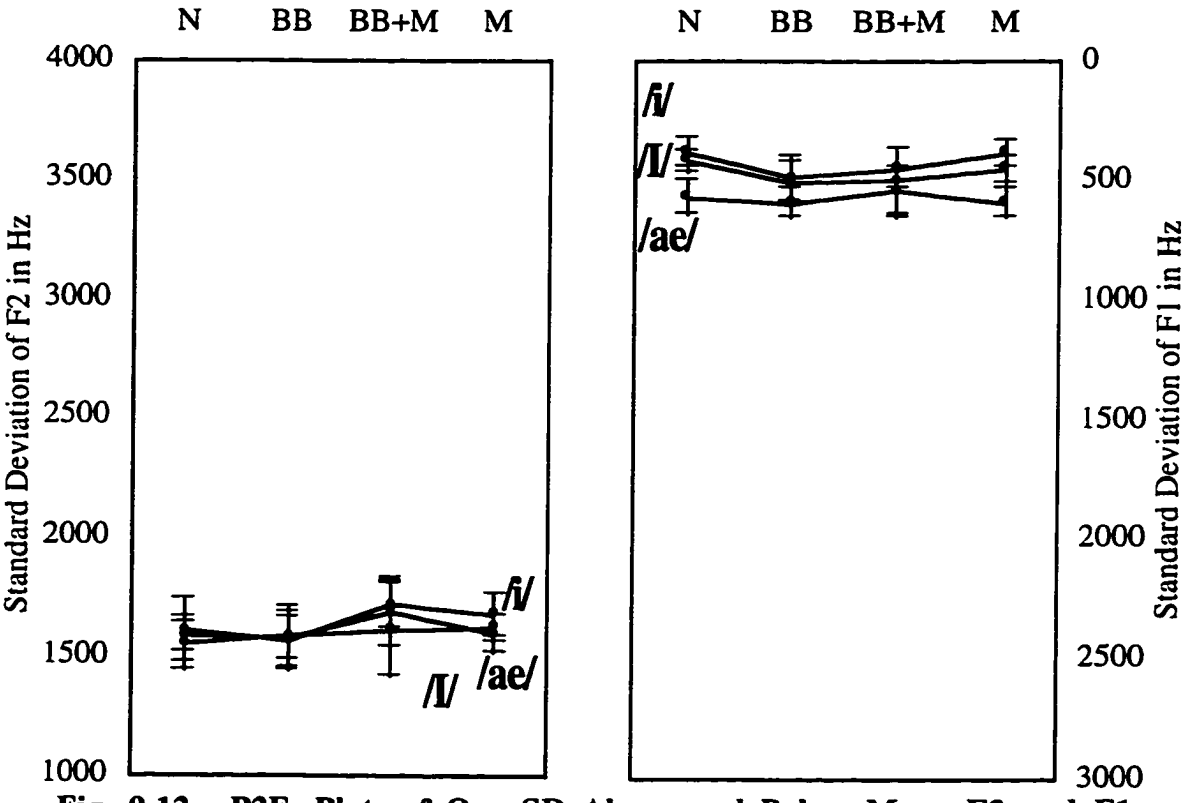
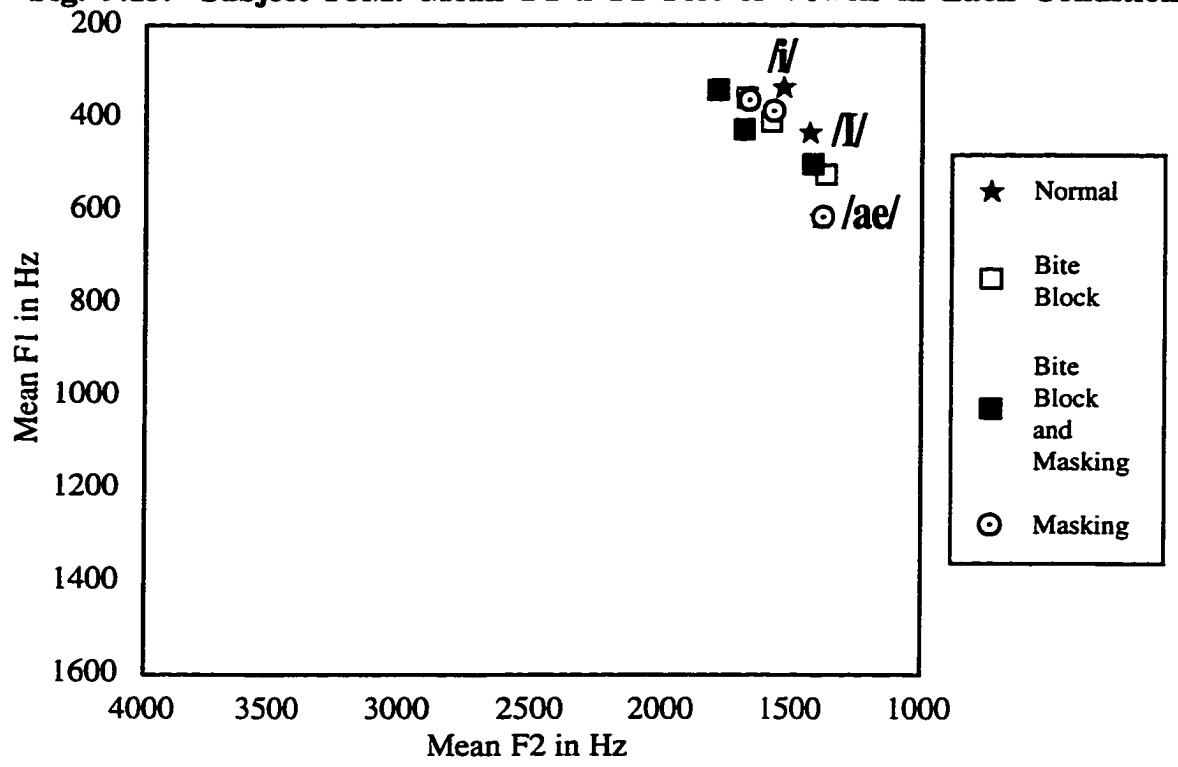


Fig. 9.12. P2F: Plots of One SD Above and Below Mean F2 and F1

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Fig. 9.13. Subject P3M: Mean F1 x F2 Plot of Vowels in Each Condition



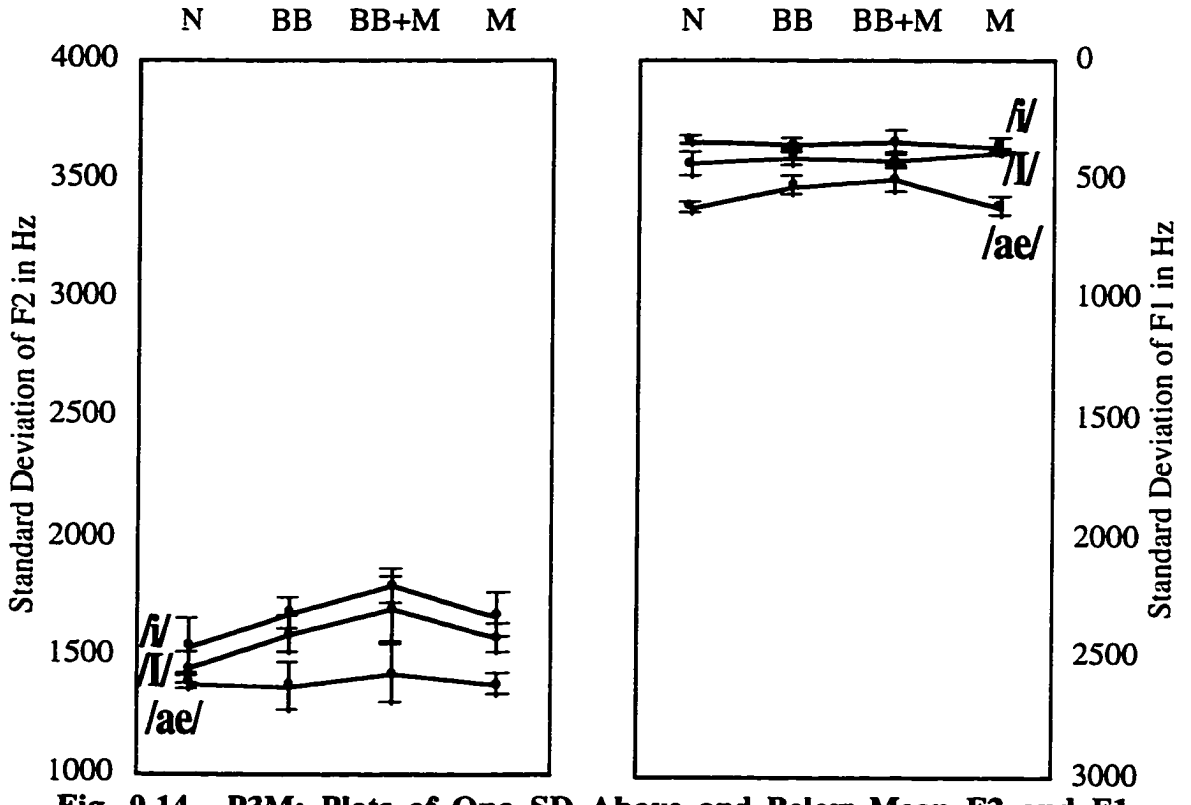
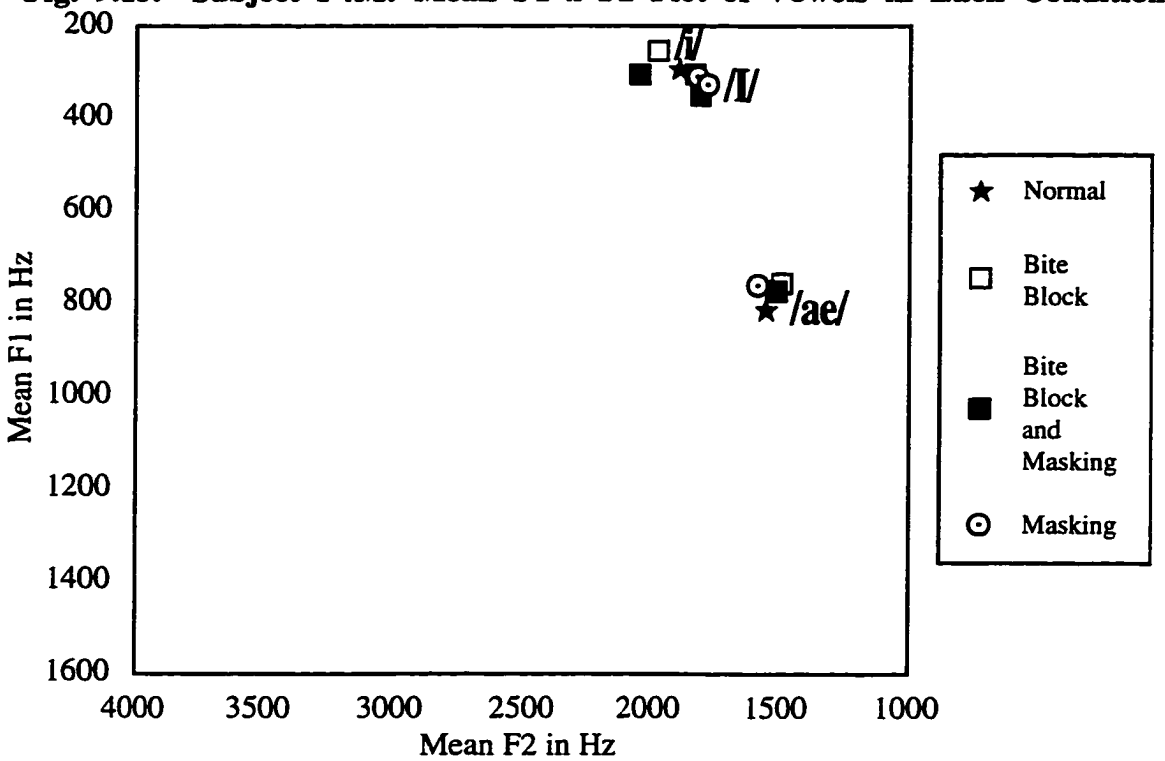


Fig. 9.14. P3M: Plots of One SD Above and Below Mean F2 and F1

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Fig. 9.15. Subject P4M: Mean F1 x F2 Plot of Vowels in Each Condition



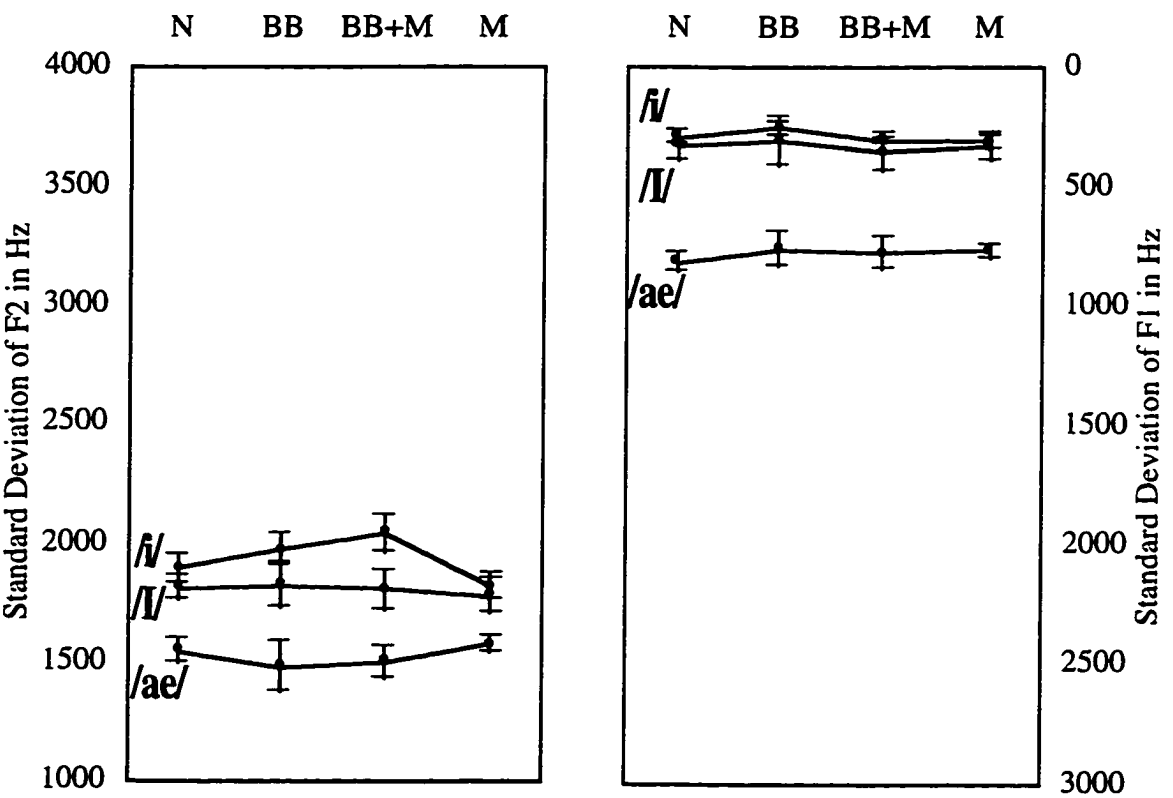
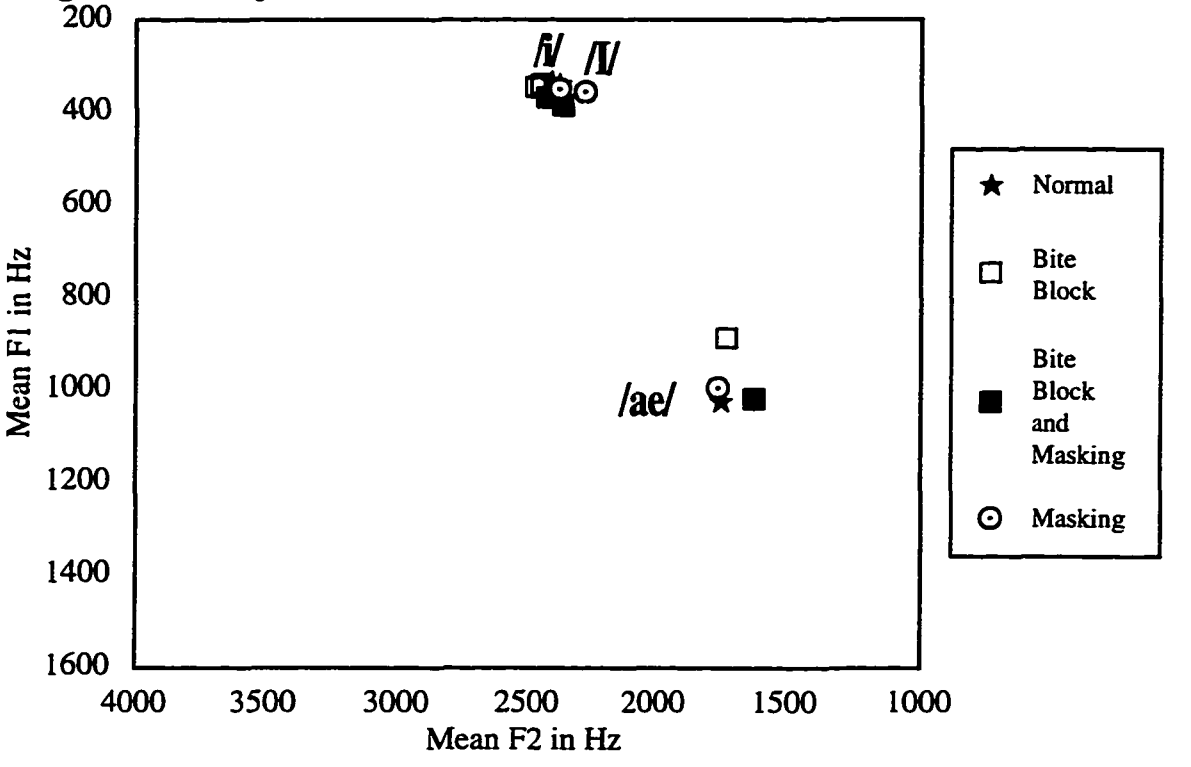


Fig. 9.16. P4M: Plots of One SD Above and Below Mean F2 and F1

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Fig. 9.17. Subject P5F: Mean F1 x F2 Plot of Vowels in Each Condition



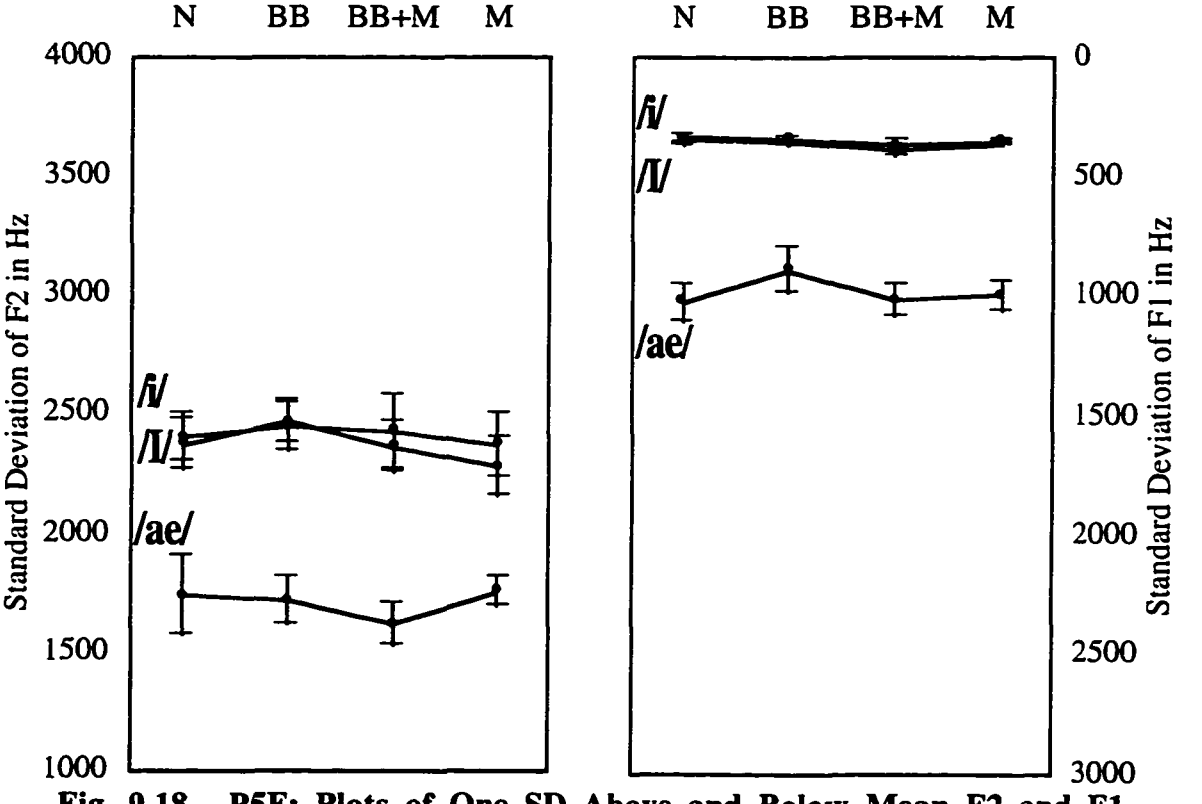
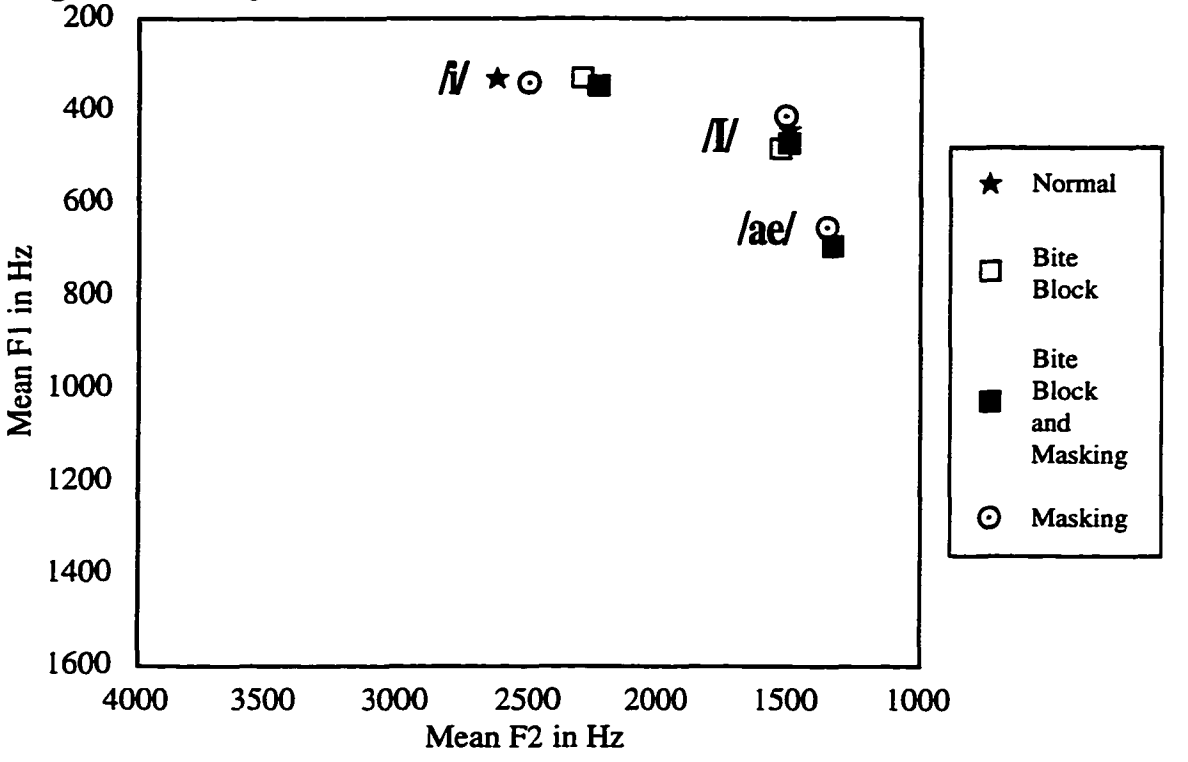


Fig. 9.18. P5F: Plots of One SD Above and Below Mean F2 and F1

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Fig. 9.19a. Subject P6M: Mean F1 x F2 Plot of Vowels in Each Condition



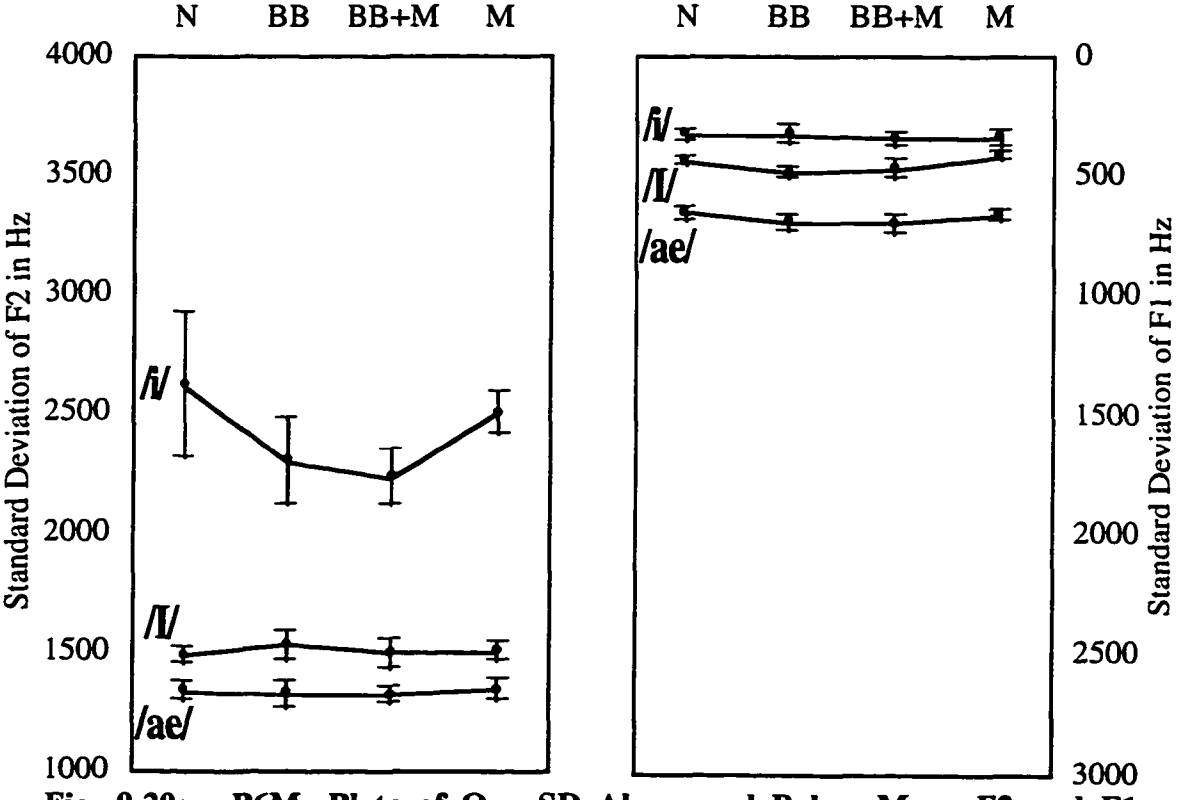
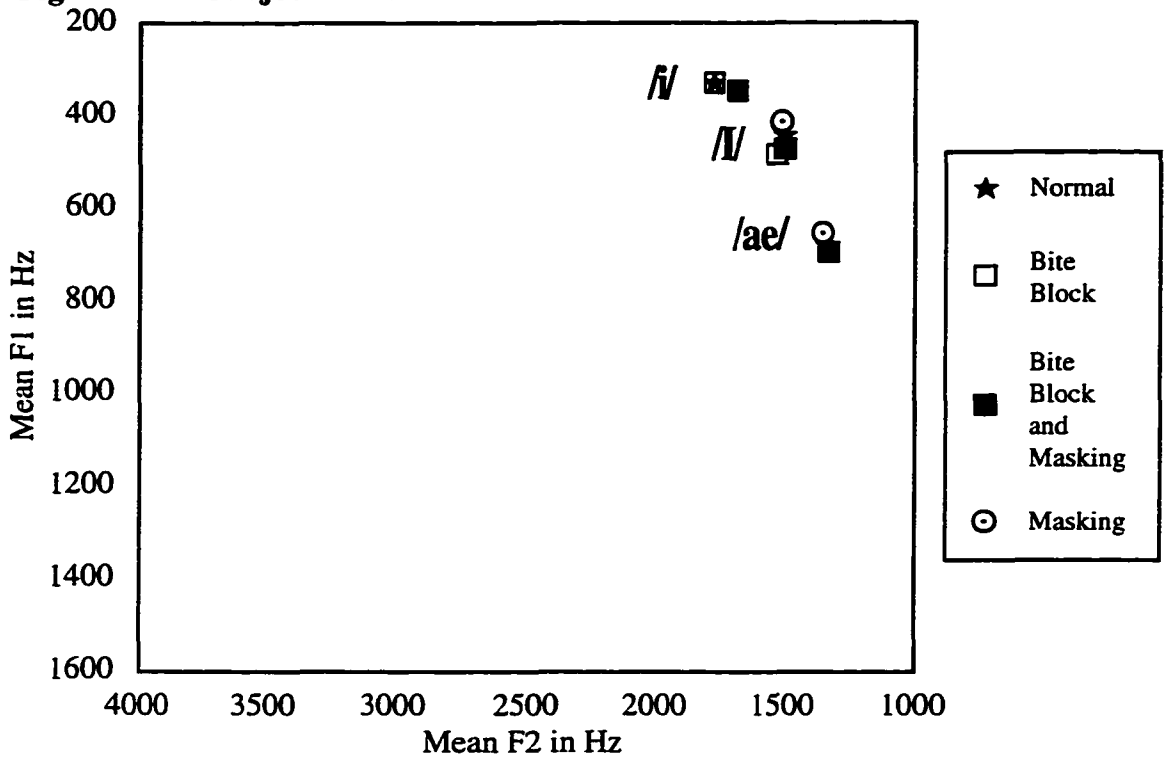


Fig. 9.20a. P6M: Plots of One SD Above and Below Mean F2 and F1

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Fig. 9.19b. Subject P6M: Mean F1 x F2 Plot of Vowels in Each Condition



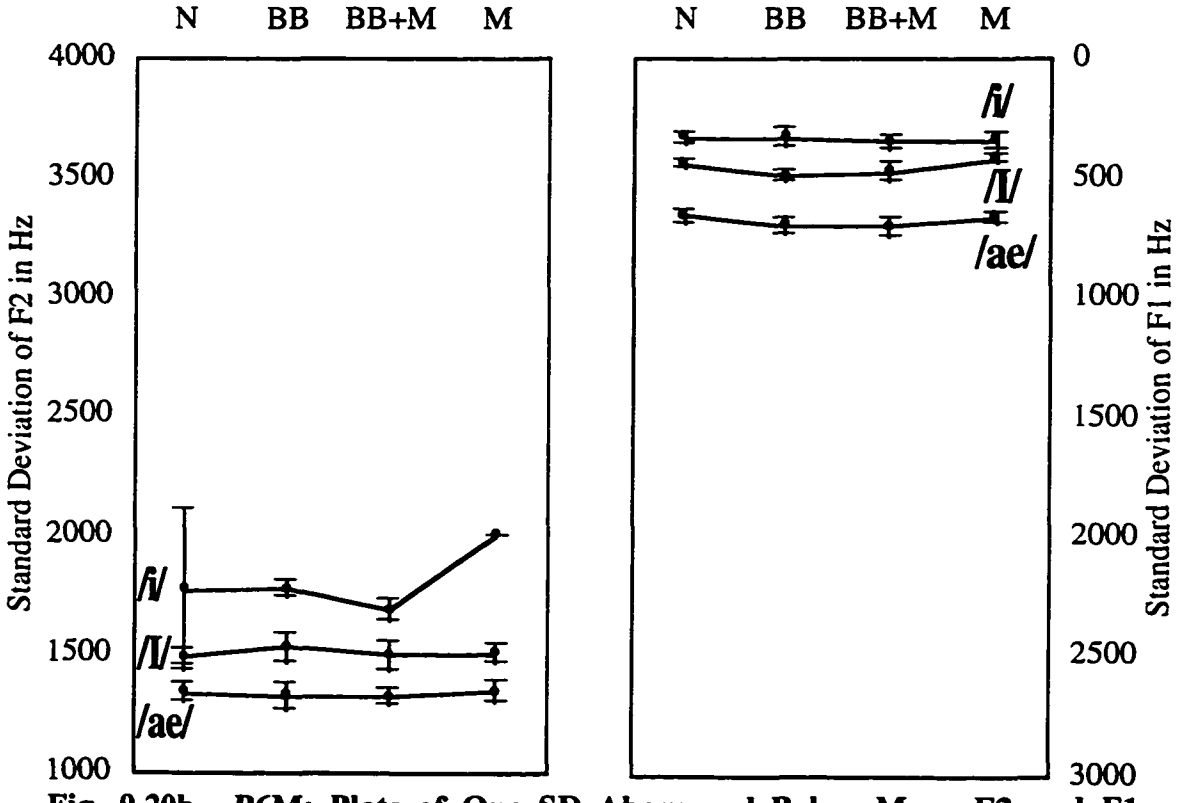


Fig. 9.20b. P6M: Plots of One SD Above and Below Mean F2 and F1

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F2

Table 9.20 shows that a significant interaction ($p<.01$) of bite-block and vowel effects on F2 was found for a majority (four of six) of the adults with profound hearing loss. The details of this interaction may be examined in a summary of Post Hoc Tukey HSD tests for unequal sample sizes in Table 9.22. For three of those four adults the high vowel /i/ showed highly significant ($p<.01$) differences in F2 between conditions where a bite block was used and conditions where it was not. P3M also showed a highly significant ($p<.01$) effect of bite block on /I/. P4M showed a highly significant ($p<.01$) effect of bite block on /ae/ F2.

Table 9.20 displays a significant interaction of masking and vowel effects for only one profoundly hearing-impaired individual, P3M. The details of this interaction may be examined in a summary of Post Hoc Tukey HSD tests for unequal sample sizes in Table 9.24. The vowels /i/ and /I/ showed highly significant ($p<.01$) differences in F2 between conditions where masking was and was not used.

Table 9.20 shows a significant ($p<.05$) interaction of bite-block, masking and vowel effects on F2 for two profoundly hearing-impaired adults, P1M and P4M. The details of this interaction may be examined in a summary of Post Hoc Tukey HSD tests for unequal sample sizes in Table 9.26. Subject P1M showed a very interesting and identical pattern of interactions for all three vowels: a highly significant difference between the masking condition and each of the other three conditions! (Cf. Table 9.10 and Figures 9.3 and 9.9.) The masking condition significantly ($p<.01$) raised F2, whereas bite-block conditions did not result in significant changes from normal. Significant interactions for P4M resulted largely from masking effects moving F2 in the opposite direction of bite-block effects for /i/ and /ae/. (See Figure 9.15).

Only P3M showed a significant ($p<.05$) interaction of bite block and vowel on F2 variability. (See Table 9.20.) Post Hoc Tukey HSD tests were conducted, but no meaningful significant comparisons were found. Only P5F showed a significant ($p<.05$)

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interaction of masking and vowel on F2 variability. (See Table 9.20.) Post Hoc Tukey HSD tests were conducted, but, again, no meaningful significant comparisons were found.

Table 9.20.--Summary of Significant Interactions of Effects on F2 and F2 Standard Deviation in Individual Adults with Profound Hearing Loss

Significant Interactions of Effects on F2						
	P1M	P2F	P3M	P4M	P5F	P6M
Interaction of Bite Block and Vowel			★★	★★	★★	★★
Interaction of Masking and Vowel			★★			
Interaction of Bite Block, Masking, and Vowel	★			★		
Significant Interactions of Effects on F2 Standard Deviation						
	P1M	P2F	P3M	P4M	P5F	P6M
Interaction of Bite Block and Vowel			★			
Interaction of Masking and Vowel					★	

★★=p<.01, ★=p<.05

F1

Changes in F1, as a result of interactions of test condition and vowel target, were exhibited by a majority of the adults with profound hearing loss. Significant interactions and subsequent post hoc tests are summarized in Tables 9.21, 9.22, 9.23, 9.24, 9.25 and 9.27.

Table 9.21 shows that a highly significant interaction (p<.01) of bite-block and vowel effects on F1 was found for a majority of the adults with profound hearing loss. The details of this interaction may be examined in a summary of Post Hoc Tukey HSD tests for unequal sample sizes in Table 9.22. A majority of the subjects showed significant (p<.01) differences in hat F1 between conditions where a bite block was and was not used. F1 in

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/i/ showed little effect of the bite block, but half of the subjects showed significant ($p<.01$) effects of bite block on /I/ F1.

Table 9.21.--Summary of Significant Interactions of Effects on F1 and F1 Standard Deviation in Individual Adults with Profound Hearing Loss

Significant Interactions of Effects on F1						
	P1M	P2F	P3M	P4M	P5F	P6M
Interaction of Bite Block and Vowel	★★	★★	★★		★★	★★
Interaction of Masking and Vowel	★★			★		★★
Interaction of Bite Block, Masking, and Vowel			★★		★★	
Significant Interactions of Effects on F1 Standard Deviation						
	P1M	P2F	P3M	P4M	P5F	P6M
Interaction of Bite Block and Vowel	★					
Interaction of Masking and Vowel						

★★=$p<.01$, ★=$p<.05$

Table 9.21 displays a significant interaction (a minimum of $p<.05$) of masking and vowel effects on F1 in half of the adults with profound hearing loss, but Post Hoc Tukey HSD tests for unequal sample sizes failed to reveal meaningful significant comparisons.

Table 9.21 shows a significant ($p<.01$) interaction of bite-block, masking and vowel effects on F1 for P3M and P5F. The details of these interactions may be examined in a summary of Post Hoc Tukey HSD tests for unequal sample sizes in Table 9.27. Heat and hit F1 were not changed significantly by test conditions, but F1 for hat was particularly affected by the bite-block and bite-block-plus-masking conditions. For P3M, these conditions significantly raised hat F1 from the normal condition and the masking condition, which had little effect. (See Figure 9.13.). For P5F, the bite-block condition significantly

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raised hat F1 from the normal condition and the other two test conditions, which had little effect. (See Figure 9.17.)

Table 9.21 shows that P1M exhibited a significant interaction of bite block and vowel on F1 variability. The post hoc tests of this interaction (See Table 9.23.) revealed that /i/ variability in bite-block conditions (Mean F1SD = 44.28) was greater than in non-bite-block conditions (Mean F1SD = 27.89), p = .0055. (See Table 9.10.)

Table 9.22.--Summary of Post Hoc Tests of Significant Interactions of Bite-Block and Vowel Effects on F2 and F1 (Collapsed Across Masking) for Individual Adults with Profound Hearing Loss

Significant Differences in F2						
Condition and Vowel	P1M	P2F	P3M	P4M	P5F	P6M
No Bite-Block "heat" vs. Bite-Block "heat"			↑ ★★	↑ ★★		↓ ★★
No Bite-Block "hit" vs. Bite-Block "hit"			↑ ★★			
No Bite-Block "hat" vs. Bite-Block "hat"				↓ ★★		
Significant Differences in F1						
Condition and Vowel	P1M	P2F	P3M	P4M	P5F	P6M
No Bite-Block "heat" vs. Bite-Block "heat"		↑ ★★				
No Bite-Block "hit" vs. Bite-Block "hit"	↓ ★★	↑ ★★				↑ ★★
No Bite-Block "hat" vs. Bite-Block "hat"	↑ ★★		↓ ★★		↓ ★★	↑ ★★

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Table 9.23.--Summary of Post Hoc Tests of Significant Interactions of Bite-Block and Vowel Effects on F2 SD and F1 SD (Collapsed Across Masking) for Individual Adults with Profound Hearing Loss

Significant Differences in F2 Standard Deviation						
Condition and Vowel	P1M	P2F	P3M	P4M	P5F	P6M
No Bite-Block "heat" vs. Bite-Block "heat"						
No Bite-Block "hit" vs. Bite-Block "hit"						
No Bite-Block "hat" vs. Bite-Block "hat"						
Significant Differences in F1 Standard Deviation						
Condition and Vowel	P1M	P2F	P3M	P4M	P5F	P6M
No Bite-Block "heat" vs. Bite-Block "heat"	★★					
No Bite-Block "hit" vs. Bite-Block "hit"						
No Bite-Block "hat" vs. Bite-Block "hat"						

★★=p<.01, ★=p<.05; ↑ = raised formant, ↓ = lowered formant

Table 9.24.--Summary of Post Hoc Tests of Significant Interactions of Masking and Vowel Effects on F2 and F1 (Collapsed Across Bite Block) for Individual Adults with Profound Hearing Loss

Significant Differences in F2						
Condition and Vowel	P1M	P2F	P3M	P4M	P5F	P6M
No Masking "heat" vs. Masking "heat"			↑ ★★			
No Masking "hit" vs. Masking "hit"			↑ ★★			
No Masking "hat" vs. Masking "hat"						
Significant Differences in F1						
Condition and Vowel	P1M	P2F	P3M	P4M	P5F	P6M
No Masking "heat" vs. Masking "heat"						
No Masking "hit" vs. Masking "hit"						
No Masking "hat" vs. Masking "hat"						

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Table 9.25.--Summary of Post Hoc Tests of Significant Interactions of Masking and Vowel Effects on F2 SD and F1 SD (Collapsed Across Bite Block) for Individual Adults with Profound Hearing Loss

Significant Differences in F2 Standard Deviation						
Condition and Vowel	P1M	P2F	P3M	P4M	P5F	P6M
No Masking "heat" vs. Masking "heat"						
No Masking "hit" vs. Masking "hit"						
No Masking "hat" vs. Masking "hat"						
Significant Differences in F1 Standard Deviation						
Condition and Vowel	P1M	P2F	P3M	P4M	P5F	P6M
No Masking "heat" vs. Masking "heat"						
No Masking "hit" vs. Masking "hit"						
No Masking "hat" vs. Masking "hat"						

★★=p<.01, ★=p<.05; ↑ = raised formant, ↓ = lowered formant

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Table 9.26.--Summary of Post Hoc Tests of Significant Interactions of Bite-Block, Masking, and Vowel Effects on F2 for Individual Adults with Profound Hearing Loss

Significant Differences in F2						
Condition and Vowel	P1M	P2F	P3M	P4M	P5F	P6M
Normal "heat" vs. Bite-Block "heat"						
Normal "heat" vs. Bite-Block-plus-Masking "heat"				★★		
Normal "heat" vs. Masking "heat"	★★					
Masking "heat" vs. Bite-Block "heat"	★★			★★		
Masking "heat" vs. Bite-Block-plus-Masking "heat"	★★			★★		
Bite Block "heat" vs. Bite-Block-plus-Masking "heat"						
Normal "hit" vs. Bite-Block "hit"						
Normal "hit" vs. Bite-Block-plus-Masking "hit"						
Normal "hit" vs. Masking "hit"	★★					
Masking "hit" vs. Bite-Block "hit"	★★					
Masking "hit" vs. Bite-Block-plus-Masking "hit"	★★					
Bite Block "hit" vs. Bite-Block-plus-Masking "hit"						
Normal "hat" vs. Bite-Block "hat"						
Normal "hat" vs. Bite-Block-plus-Masking "hat"						
Normal "hat" vs. Masking "hat"	★★					
Masking "hat" vs. Bite-Block "hat"	★★			★		
Masking "hat" vs. Bite-Block-plus-Masking "hat"	★★					
Bite Block "hat" vs. Bite-Block-plus-Masking "hat"						

★★=p<.01, ★=p<.05; direction of change illustrated in Figures 9.21 - 9.23

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Table 9.27.--Summary of Post Hoc Tests of Significant Interactions of Bite-Block, Masking, and Vowel Effects on F1 for Individual Adults with Profound Hearing Loss

Significant Differences in F1						
Condition and Vowel	P1M	P2F	P3M	P4M	P5F	P6M
Normal "heat" vs. Bite-Block "heat"						
Normal "heat" vs. Bite-Block-plus-Masking "heat"						
Normal "heat" vs. Masking "heat"						
Masking "heat" vs. Bite-Block "heat"						
Masking "heat" vs. Bite-Block-plus-Masking "heat"						
Bite Block "heat" vs. Bite-Block-plus-Masking "heat"						
Normal "hit" vs. Bite-Block "hit"						
Normal "hit" vs. Bite-Block-plus-Masking "hit"						
Normal "hit" vs. Masking "hit"						
Masking "hit" vs. Bite-Block "hit"						
Masking "hit" vs. Bite-Block-plus-Masking "hit"						
Bite Block "hit" vs. Bite-Block-plus-Masking "hit"						
Normal "hat" vs. Bite-Block "hat"			★★		★★	
Normal "hat" vs. Bite-Block-plus-Masking "hat"			★★			
Normal "hat" vs. Masking "hat"						
Masking "hat" vs. Bite-Block "hat"			★★		★★	
Masking "hat" vs. Bite-Block-plus-Masking "hat"			★★			
Bite Block "hat" vs. Bite-Block-plus-Masking "hat"					★★	

★★=p<.01, ★=p<.05; direction of change illustrated in Figures 9.21 - 9.23

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Summary

Tables 9.28 - 9.31 facilitate the comparison of bite-block, masking, and bite-block-plus-masking effects on all dependent variables, to show patterns revealed by the majority of individual talkers within and across each subject group. Columns for results from subsequent chapters appear in gray now.

The data from individual adults with profound hearing loss revealed that:

A. There was a significant ($p<.01$) main effect of bite block on F2 for a majority of these subjects. (See Table 9.28.) (All the adults and the children with normal hearing had shown a significant main effect of bite block.) Range of percent-change in formants was more restricted than that of either the adults or the children with normal hearing. As with the children, /i/ was most often affected by the bite block. One of the most interesting findings is the contrast in direction of change between these subjects and those with normal hearing. While computer simulation predicted, and data from the other two subject groups showed, a lowering of F2 in the bite-block condition, these talkers raised F2 in /I/ and raised F2 as often as it was lowered for /i/. The direction of change does not suggest a failure to compensate, but, in fact, some overcompensation for the close vowels. A significant main effect of bite block on F1 was shown in half of these subjects. (A majority of the adults and the children with normal hearing had shown a significant main effect of bite block.) For F1, the range of percent-change was equivalent to that of the adults with normal hearing, and, like the subjects with normal hearing, hat F1 was differentially affected. Again, direction of change in F1 is different from that in the subjects with normal hearing. While /i/ F1 is raised, as predicted by computer simulation and seen in the other subjects, F1 moved in both directions for the other vowels. Jaw movements of others can be perceived through speechreading and thus may be used to a greater extent by some hearing-impaired speakers to differentiate vowels in their own production. Larger jaw excursions used

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in everyday speech could lead to bite-block formant changes in directions not predicted by computer simulation for typical speakers.

B. A main effect of masking on F2 was found for a majority of these profoundly hearing-impaired subjects! (See Table 9.29.) In this respect, the results are surprisingly similar to the findings in the individual adults with normal hearing! Furthermore, the range of percent change in F2 in this condition was greater than that for the subjects with normal hearing. However, once again, direction of change is in contrast. While adults with normal hearing consistently lowered F2 in masking, these subjects showed a pattern of raising. For F1 there was no main effect of masking found for a majority of talkers, as there had been in the subjects with normal hearing. Range of percent change was also restricted compared to the other subject groups. Direction of change was the same for /i/ across this and other subject groups, but unclear for the other two vowels. The difference in results for F2 and F1 in the masking condition may be the consequence of a greater auditory dependence to monitor tongue movements that influence F2 and a greater visual dependence in setting the jaw excursions that influence F1.

C. No significant interaction of bite block and masking was found. (See Table 9.30.) Range of percent change was comparable to that in the adults with normal hearing. Again, the interesting finding was in the direction of change. The profoundly hearing-impaired adults displayed a general pattern of raising F2 in the close vowels, different from the lowering pattern of the other groups and predicted by computer simulation. The direction of change suggests an "overcompensation" response. Conversely, the direction of change in F1 was very similar to that of the individuals in the other groups and range of percent change was comparable, if not slightly more restricted. A significant interaction of bite block and masking was found in half of these subjects, but post hoc tests revealed that F1 was more affected by the bite-block condition than bite-block-plus-masking. This was opposite of the findings in the adults with normal hearing who showed larger F1 changes in the masking and the bite-block-plus-masking

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condition than in the bite-block condition alone. Figures 9.21 - 9.23 provide an overview of direction and magnitude of formant changes in every individual adult with profound hearing loss. Where subjects exhibited a significant interaction of bite block, masking and vowel, post hoc tests were conducted for differences. (See Tables 9.20, 9.21, 9.26, and 9.27.) Those post hoc tests that showed significant differences between normal and test conditions are identified by stars in Figures 9.21 - 9.23.

D. Test conditions did not result in changes in variability of production for F2, but a main effect of bite block was found for a majority of these individuals for F1 standard deviation. (See Table 9.31.) No other group of individual talkers showed a pattern of less F1 stability as an effect of bite block. However, just like individuals in the other subject groups, half of the adults with profound hearing loss showed a significant main effect of vowel for F1. F1 was most variable in hat, less so in hit, and least in heat, collapsed across condition.

E. Individual subjects varied in their ability to compensate in test conditions. One of the more interesting findings in this regard was the significant effect of masking on F2 for every vowel produced by subject P1M. (See Figures 9.21 - 9.23.)

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Table 9.28.--Summary of Bite-Block Effects on F2 and F1 for the Majority of Individual Subjects

	Adults with Normal Hearing	**Children with Normal Hearing**	**Adults with Profound Hearing Loss**	Adults with Severe Hearing Loss
F2 Direction of Change: heat hit hat	 lowered lowered lowered	 lowered lowered lowered	 unclear raised lowered	
Range of % Change	.23 - 16.58%	.22 - 24.48	.48 - 12.21	
Main Effect of Bite Block	★★(all)	★/★★(all)	★★	
BB-by-Vowel Interaction	★/★★	★/★★(half)	★★	
Details of Interaction:	individual variation in affected vowel targets	/i/ most often affected; /I/ also, but less often	/i/ most often affected	
F1 Direction of Change: heat hit hat	 raised raised lowered	 raised raised lowered	 raised unclear unclear	
Range of % Change	.38 - 24.25%	1.85 - 40.43	.05 - 26.28	
Main Effect of Bite Block	★/★★	★/★★	★★(half)	
BB-by-Vowel Interaction	★/★★(all)	★/★★	★★	
Details of Interaction:	hat most often affected	hat most often affected	hat most often affected	

★★=p<.01, ★=p<.05

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Table 9.29.--Summary of Masking Effects on F2 and F1 for the Majority of Individual Subjects

	Adults with Normal Hearing	**Children with Normal Hearing**	**Adults with Profound Hearing Loss**	Adults with Severe Hearing Loss
F2 Direction of Change: heat hit hat	 lowered lowered lowered	 lowered raised unclear	 unclear raised raised	
Range of % Change	.43 - 5.4%	.15 - 6.09	.36 - 13.18	
Main Effect of Masking	★/★★		★/★★	
M-by-Vowel Interaction	★/★★			
Details of Interaction:	N1M and N6M particularly affected by masking for all vowels			
F1 Direction of Change: heat hit hat	 raised raised raised	 raised raised unclear	 raised unclear unclear	
Range of % Change	.22 - 18.8%	.35 - 33.68	.15 - 10.89	
Main Effect of Masking	★/★★(all)	★/★★		
M-by-Vowel Interaction	★/★★	★/★★(half)	★/★★(half)	
Details of Interaction:	heat and hit most often affected	hat most often affected	no meaningful patterns shown	

★★=p<.01, ★=p<.05

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Table 9.30.--Summary of Bite-Block-Plus-Masking Effects on F2 and F1 for the Majority of Individual Subjects

	Adults with Normal Hearing	**Children with Normal Hearing**	**Adults with Profound Hearing Loss**	Adults with Severe Hearing Loss
F2 Direction of Change:				
heat	lowered	lowered	raised	
hit	lowered	lowered	unclear	
hat	lowered	lowered	lowered	
Range of % Change	.66 - 16.71%	.52 - 13.88	.51 - 17.36	
Interaction of BB and M				
Interaction of BB and M and Vowel	★/★★			
Details of Interactions:				
heat	affected more by B+M than by BB or M alone			
hit	no overall pattern			
hat	affected more by B+M than by BB or M alone			
F1 Direction of Change:				
heat	raised	raised	raised	
hit	raised	raised	raised	
hat	raised	lowered	lowered	
Range of % Change	.44 - 36.67%	1.9 - 45.41	.53 - 27.53	
Interaction of BB and M	★/★★		★/★★(half)	
Interaction of BB and M and Vowel	★/★★			
Details of Interactions:				
in general	M and B+M more detrimental than BB alone			
heat	little effect			
hit	B+M detrimental for N4F and N6M			
hat	BB and B+M more detrimental than masking alone			

★★=p<.01, ★=p<.05

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Table 9.31.--Summary of All Test Effects on F2 and F1 Variability for the Majority of Individual Subjects

	Adults with Normal Hearing	**Children with Normal Hearing**	**Adults with Profound Hearing Loss**	Adults with Severe Hearing Loss
Main Effect of Bite Block		↑ ★/★★(half)		
Interaction of BB and V				
Main Effect of Masking				
Interaction of M and V				
Interaction of BB and M				
Main Effect of Vowel				
Details of Interactions:				
Main Effect of Bite Block			↑ ★/★★	
Interaction of BB and V				
Main Effect of Masking				
Interaction of M and V				
Interaction of BB and M				
Main Effect of Vowel	★/★★(all)	★/★★(half)	★★(half)	
Details of Interactions:				
heat	least variability	least variability	least variability	
hit	more variability	more variability	more variability	
hat	greatest variability	greatest variability	greatest variability	

★★=p<.01, ★=p<.05; ↑ = increased variability, ↓ = decreased variability

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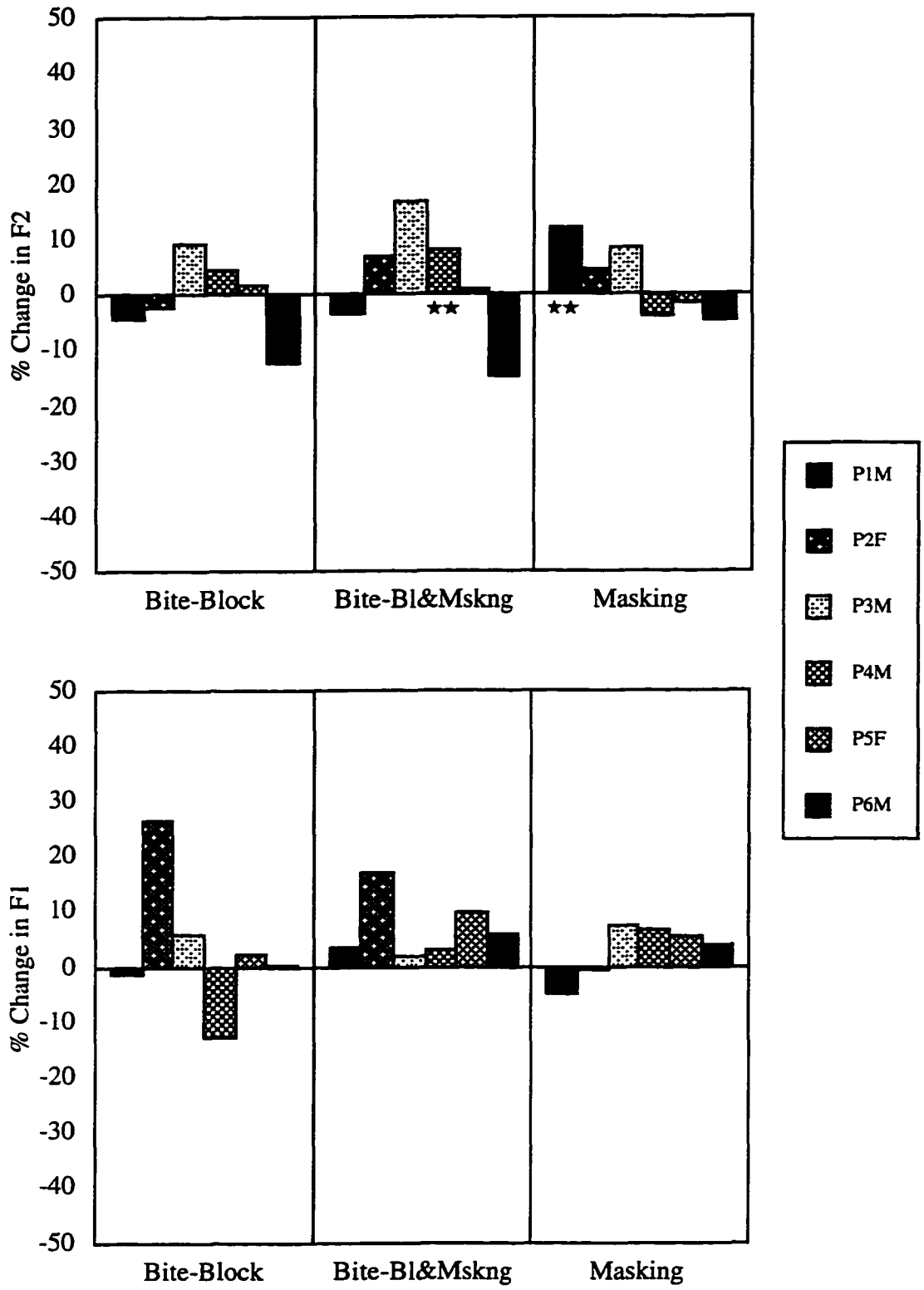


Fig. 9.21. Overview of Changes in F2 and F1 in /i/ for Each Adult with Profound Hearing Loss

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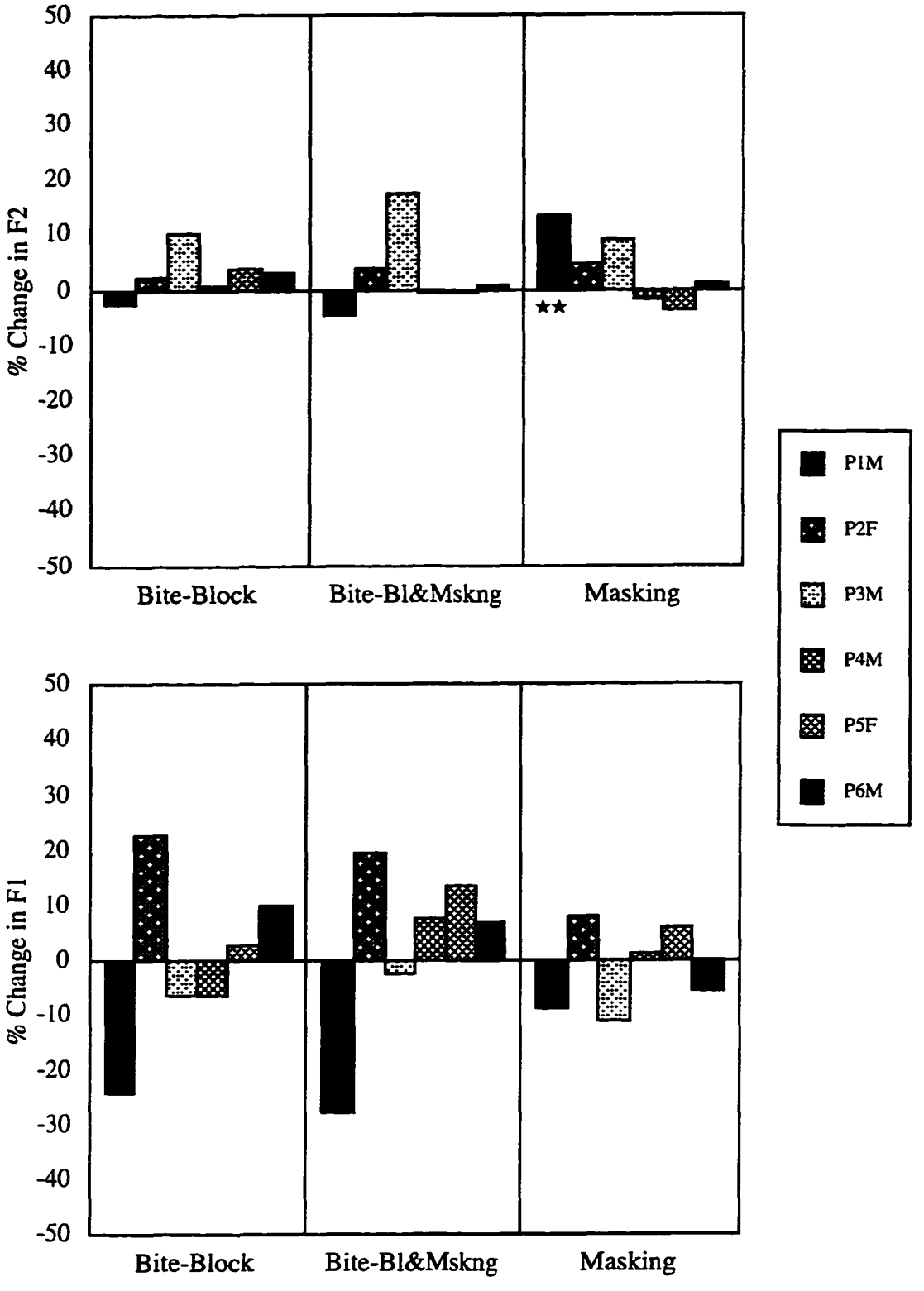


Fig. 9.22. Overview of Changes in F2 and F1 in /I/ for Each Adult with Profound Hearing Loss

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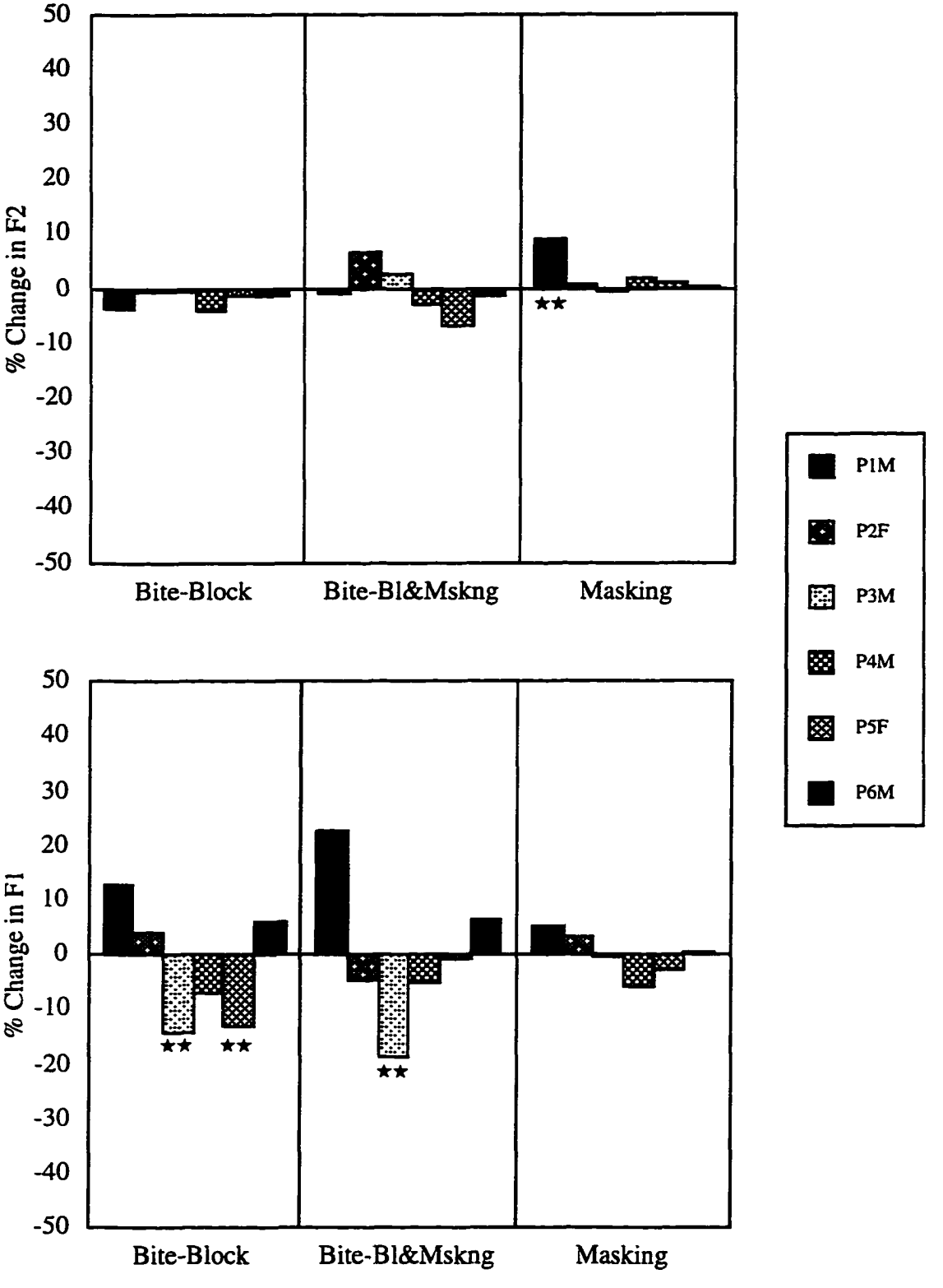


Fig. 9.23. Overview of Changes in F2 and F1 in /ae/ for Each Adult with Profound Hearing Loss

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Summary of Results from Adults with Profound Hearing Loss

Bite-Block Effects

The bite block lowered F2 in /i/ and /ae/ for the group, as predicted by computer simulation, but raised it in /I/. Investigating the direction of change in individuals showed that F2 was raised in /i/ as often as it was lowered. Taking the two sets of data together, there is a suggestion that there was a pattern of raising, rather than lowering, of F2 in the close vowels. The range of percent change in F2 was modest. Indeed, the group showed no significant effects of bite block, but a majority of individuals did. /i/ was most often the vowel target where greatest F2 change was seen with the bite block. However, for some of these individuals, F2 was significantly raised from the normal condition, not lowered. Taken together, these findings suggest that there was a pattern of overcompensation, rather than failure to compensate, most certainly when the target was /I/, and sometimes when the target was /i/.

The bite block raised F1 in /i/, as predicted by computer simulation, but lowered it for /I/ and /ae/ for the group. Individual articulatory patterns also showed that F1 in /i/ was raised, but the pattern for /I/ and /ae/ was unclear, given that F1 was lowered in as many cases as it was raised. While the group showed no significant effect of bite block on F1, half of the individuals did, with /ae/ most often the target that showed greatest changes in the bite-block condition. These talkers may use larger jaw excursions for open vowels in their normal speech than do speakers with normal hearing. Thus a bite-block might result in more cases of formant lowering.

The largest difference between the findings for the adults with profound hearing loss and the adults and children with normal hearing is direction of change. For F2 there was convincing evidence of formant raising, not lowering, suggesting instances of overcompensation for the close vowels. There was no evidence to suggest that the bite block was more detrimental to the production of this group than to talkers with normal hearing. In fact, range of percent change was comparable or smaller. There were, in fact,

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more significant findings of effect of bite block in the adults and the children with normal hearing.

Masking Effects

The masking condition, like the bite-block condition, resulted in a pattern of F2 raising in the group and in a majority of individuals. Again, range of percent change was small, but it is extremely interesting that there is a change in production with the removal of hearing aids and the introduction of masking noise, that was delivered at an intensity level that was often below the auditory threshold of many of these speakers. Indeed, a majority of the individual adults with profound hearing loss showed a significant main effect of masking on F2!

While F1 was raised for /i/, formant changes in /I/ and /ae/ were in both directions. A main effect of masking was not shown for F1, as it was for F2. It may be that auditory feedback is necessary to monitor anterior/posterior movements of the tongue affecting F2, but visual and kinesthetic feedback can guide jaw height, affecting F1.

In comparing masking effects across all subject groups and individuals, it is interesting to note that the children showed no significant effects of masking on F2, but adults with normal hearing and adults with profound hearing loss did! With F1, on the other hand, the individual children and the individual adults with normal hearing did show a main effect of masking, but the profoundly hearing-impaired did not, perhaps, as speculated, because jaw height may be monitored visually and kinesthetically. In addition, it is also noteworthy that in both groups of adults, the masking changes largely followed bite-block changes. That is, the bite block condition and the masking condition each produced a lowered F2 and a raised F1 in the adults with normal hearing, but a pattern of raising of F2 and F1 change in both directions for the adults with profound hearing loss.

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Bite-Block-and-Masking Interaction

The bite-block-plus-masking condition produced a pattern of a raised F2 for the high vowels, just as the bite-block and masking conditions had each done separately. There were no significant interactions of bite block and masking for the group or for individuals.

The direction of change in F1 was as predicted by computer simulation for a bite block, a raised F1 for /i/ and /I/. For the group, /ae/ was unchanged, but a majority of individuals showed a pattern of lowering. There was a significant interaction of bite block and masking for half of the individuals, but post hoc tests revealed that the bite-block condition resulted in more change in F1 than the bite-block-plus-masking condition, thus there was no evidence to suggest that bite-block effects were more detrimental in the presence of masking.

Comparing across subject groups and individuals, the adults with profound hearing loss show a pattern of F2 raising for the high vowels, not lowering, as seen with the other groups. Again, this suggests some overcompensation for these vowel targets, not a failure to compensate. Indeed, there were no significant findings for F2 or for F1 for the group or for a majority of individuals in this condition. In fact, post hoc tests of a significant interaction of bite block and masking for F1, in half of the subjects, revealed that the bite block was more detrimental than the combined condition. The adults with normal hearing, however, showed that the combined condition was more detrimental than either alone for /i/ F2 and /I/ F1. The children showed that the combined condition was more detrimental than masking alone.

Variability

While the variability of F2 was unaffected by condition, the bite block increased variability of F1 in /i/ and /ae/ and the bite-block-plus-masking condition increased /ae/ F1 standard deviation in the group. A majority of individual subjects also showed a main effect of bite block, collapsed across vowels. No other subject groups showed decreased

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stability of F1 in test conditions, but the group of adults with normal hearing showed increased variability of /ae/ F2 in the bite-block condition and half of the individual children showed a main effect of bite block on F2 standard deviation, collapsed across vowel.

Discussion of and Conclusions Drawn from These Results

It may be concluded from these results that adults with congenital profound hearing loss do not fail to compensate, but actually overcompensate for a bite block in production of close vowels, suggesting that they seek to preserve articulatory targets specified in tactile or proprioceptive terms.

It may also be concluded that auditory feedback did not play a role in compensation for a bite block in that results were similar between bite-block and bite-block-plus-masking conditions. However, the masking condition showed an effect on F2 in the same direction as in the bite-block condition, suggesting that some of the subjects used amplified residual hearing to guide tongue movement. Masking did not have an effect on F1 (tongue height) which may more easily be monitored by visual and kinesthetic feedback than F2. In fact, this was the only group of subjects that displayed more variability in F1 in the bite-block condition.

The theoretical implication of these results is that articulatory compensation is not only a property of articulatory systems with auditory speech targets. Immediate compensation may also be accomplished peripherally in articulatory systems with articulatory or gestural targets. Therefore the hypothesis that adults with profound hearing loss compensate for a bite block, as seen in adults with normal hearing, with or without auditory feedback, may be accepted, but for the phrase "as seen in adults with normal hearing". This pattern of compensation was quite different.

Given these findings it might be anticipated that the adults with severe hearing loss would compensate substantially, but not perfectly, for a bite block, as do adults with normal hearing, in that their speech targets are expected to be largely auditory, even if

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distorted. This was found to be true. The data from the adults with severe hearing loss are examined next.

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CHAPTER TEN

RESULTS: ADULTS WITH SEVERE HEARING LOSS

The application of this experiment to a group of six adults with severe hearing loss tested the fourth hypothesis of this dissertation: Adults with severe hearing loss compensate for a bite block, as seen in adults with normal hearing, and auditory feedback plays a role in this compensation.

Acoustic Analysis of Vowels Produced in Four Conditions: Measures of Articulatory Compensation

Group Data

Results were first examined using data averaged across the group of six subjects. The absolute formant frequency values used for statistical tests were recorded in Table 10.1a-c which follows ("N/A" indicates missing data). For figure presentations, percent change in formant frequency from normal to test conditions was used to illustrate changes in each of the second and first formants.

Direction of Change

The second formant measurements were averaged across the adults with severe hearing loss and examined for overall differences among conditions. The bar graphs on the left side of Figure 10.1 revealed that they exhibited changes in F2 in test conditions compared to the normal condition. Computer simulation predicted that the bite block would result in a lowering of F2 from the normal condition. With the exception of the bite-block condition for hat, F2 was lowered, as predicted. The masking condition and the bite-block-plus-masking condition also lowered F2.

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Table 10.1a.--Group Means, % Change, and Standard Deviations of F2 and F1 of "Heat" for Adults with Severe Hearing Loss

Subject	Sex	Condition	Vowel	Mean F2	%Ch in F2	Mean F1	%Ch in F1	F2 SD	F1 SD
S1M	Male	Normal	heat	2052.31	***	310.85	***	46.27	10.71
S2M	Male	Normal	heat	1994.20	***	270.80	***	51.68	26.67
S3F	Female	Normal	heat	2127.91	***	321.27	***	66.22	50.13
S4M	Male	Normal	heat	2325.54	***	311.92	***	44.44	22.86
S5F	Female	Normal	heat	N/A	***	N/A	***	N/A	N/A
S6F	Female	Normal	heat	2458.29	***	393.93	***	28.97	17.81
Group Means Per Condition				2191.65	***	321.75	***	47.52	25.64
S1M	Male	Bite-Block	heat	1884.56	-8.17	355.38	14.33	39.45	37.81
S2M	Male	Bite-Block	heat	1963.13	-1.56	297.38	9.82	64.86	18.59
S3F	Female	Bite-Block	heat	2227.25	4.67	317.83	-1.07	58.47	49.65
S4M	Male	Bite-Block	heat	2250.10	-3.24	332.40	6.57	56.21	25.38
S5F	Female	Bite-Block	heat	N/A	N/A	N/A	N/A	N/A	N/A
S6F	Female	Bite-Block	heat	2320.00	-5.63	434.80	10.37	76.88	58.00
Group Means Per Condition				2129.01	-2.79	347.56	8.00	59.17	37.89
S1M	Male	Bite-Bl&Mskng	heat	1842.60	-10.22	387.67	24.71	69.90	16.67
S2M	Male	Bite-Bl&Mskng	heat	1724.00	-13.55	345.13	27.45	124.22	35.98
S3F	Female	Bite-Bl&Mskng	heat	2237.00	5.13	376.93	17.32	66.76	42.64
S4M	Male	Bite-Bl&Mskng	heat	2038.00	-12.36	322.25	3.31	90.57	19.33
S5F	Female	Bite-Bl&Mskng	heat	N/A	N/A	N/A	N/A	N/A	N/A
S6F	Female	Bite-Bl&Mskng	heat	2262.36	-7.97	449.00	13.98	49.08	60.09
Group Means Per Condition				2020.79	-7.79	376.20	17.35	80.11	34.94
S1M	Male	Masking	heat	1986.54	-3.20	364.92	17.39	73.53	25.62
S2M	Male	Masking	heat	1843.35	-7.56	279.77	3.31	51.62	18.60
S3F	Female	Masking	heat	2096.29	-1.49	286.71	-10.76	57.72	20.36
S4M	Male	Masking	heat	2153.60	-7.39	290.80	-6.77	86.31	32.85
S5F	Female	Masking	heat	N/A	N/A	N/A	N/A	N/A	N/A
S6F	Female	Masking	heat	2414.86	-1.77	416.93	5.84	52.66	45.64
Group Means Per Condition				2098.93	-4.28	327.83	1.80	64.37	28.61

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Table 10.1b.--Group Means, % Change, and Standard Deviations of F2 and F1 of "Hit" for Adults with Severe Hearing Loss

Sub-ject	Sex	Condition	Vowel	Mean F2	%Ch in F2	Mean F1	%Ch in F1	F2 SD	F1 SD
S1M	Male	Normal	hit	1612.69	***	447.69	***	64.20	28.59
S2M	Male	Normal	hit	1639.69	***	350.19	***	112.43	45.37
S3F	Female	Normal	hit	1970.11	***	420.89	***	79.38	24.18
S4M	Male	Normal	hit	1913.64	***	475.29	***	74.83	33.96
S5F	Female	Normal	hit	2081.40	***	465.53	***	57.27	32.59
S6F	Female	Normal	hit	2222.81	***	480.56	***	82.63	90.28
Group Means Per Condition				1906.72	***	440.03	***	78.46	42.50
S1M	Male	Bite-Block	hit	1563.25	-3.07	478.81	6.95	53.33	48.25
S2M	Male	Bite-Block	hit	1526.81	-6.88	398.13	13.69	89.36	52.94
S3F	Female	Bite-Block	hit	N/A	N/A	N/A	N/A	N/A	N/A
S4M	Male	Bite-Block	hit	1971.00	3.00	460.44	-3.12	56.18	30.17
S5F	Female	Bite-Block	hit	2068.54	-0.62	516.39	10.93	92.36	28.12
S6F	Female	Bite-Block	hit	2116.07	-4.80	490.60	2.09	69.37	32.67
Group Means Per Condition				1849.13	-2.47	468.87	6.11	72.12	38.43
S1M	Male	Bite-Bl&Mskng	hit	1504.88	-6.69	479.38	7.08	79.18	42.13
S2M	Male	Bite-Bl&Mskng	hit	1468.93	-10.41	436.00	24.50	69.29	44.75
S3F	Female	Bite-Bl&Mskng	hit	2094.88	6.33	416.75	-0.98	109.15	37.60
S4M	Male	Bite-Bl&Mskng	hit	1664.79	-13.00	523.57	10.16	79.00	38.66
S5F	Female	Bite-Bl&Mskng	hit	1965.29	-5.58	486.71	4.55	175.21	20.82
S6F	Female	Bite-Bl&Mskng	hit	2058.00	-7.41	504.38	4.96	65.41	37.58
Group Means Per Condition				1792.80	-6.13	474.47	8.38	96.21	36.92
S1M	Male	Masking	hit	1520.69	-5.70	492.31	9.97	40.78	47.65
S2M	Male	Masking	hit	1638.63	-0.06	360.81	3.03	128.96	40.72
S3F	Female	Masking	hit	1977.10	0.35	425.60	1.12	160.63	31.94
S4M	Male	Masking	hit	1719.00	-10.17	525.14	10.49	64.09	31.68
S5F	Female	Masking	hit	2058.13	-1.12	447.00	-3.98	47.81	22.89
S6F	Female	Masking	hit	2199.63	-1.04	449.50	-6.46	63.06	44.37
Group Means Per Condition				1852.20	-2.96	450.06	2.36	84.22	36.54

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Table 10.1c.--Group Means, % Change, and Standard Deviations of F2 and F1 of "Hat" for Adults with Severe Hearing Loss

Subject	Sex	Condition	Vowel	Mean F2	%Ch in F2	Mean F1	%Ch in F1	F2 SD	F1 SD
S1M	Male	Normal	hat	1420.81	***	670.63	***	36.22	52.71
S2M	Male	Normal	hat	1359.06	***	536.38	***	63.95	38.49
S3F	Female	Normal	hat	1750.20	***	872.67	***	81.05	50.07
S4M	Male	Normal	hat	1623.94	***	917.25	***	61.03	51.78
S5F	Female	Normal	hat	1719.00	***	876.31	***	92.29	62.33
S6F	Female	Normal	hat	1681.19	***	934.75	***	287.51	54.62
Group Means Per Condition				1592.37	***	801.33	***	103.68	51.67
S1M	Male	Bite-Block	hat	1471.33	3.56	754.67	12.53	57.78	74.42
S2M	Male	Bite-Block	hat	1352.00	-0.52	535.38	-0.19	40.63	61.04
S3F	Female	Bite-Block	hat	1974.13	12.79	916.94	5.07	64.14	50.19
S4M	Male	Bite-Block	hat	1621.73	-0.14	898.33	-2.06	138.01	44.81
S5F	Female	Bite-Block	hat	1749.21	1.76	1010.50	15.31	102.68	74.11
S6F	Female	Bite-Block	hat	1727.50	2.75	911.88	-2.45	71.45	31.92
Group Means Per Condition				1649.32	3.37	837.95	4.70	79.12	56.08
S1M	Male	Bite-Bl&Msknng	hat	1361.25	-4.19	699.63	4.32	69.37	49.78
S2M	Male	Bite-Bl&Msknng	hat	1345.38	-1.01	516.00	-3.80	44.89	30.17
S3F	Female	Bite-Bl&Msknng	hat	1592.69	-9.00	818.56	-6.20	117.83	59.33
S4M	Male	Bite-Bl&Msknng	hat	1444.25	-11.07	819.81	-10.62	51.15	43.22
S5F	Female	Bite-Bl&Msknng	hat	1712.94	-0.35	826.69	-5.66	109.33	85.18
S6F	Female	Bite-Bl&Msknng	hat	1555.75	-7.46	902.69	-3.43	64.37	33.53
Group Means Per Condition				1502.04	-5.51	763.90	-4.23	76.16	50.20
S1M	Male	Masking	hat	1401.81	-1.34	708.44	5.64	46.52	39.75
S2M	Male	Masking	hat	1313.00	-3.39	529.20	-1.34	57.17	66.16
S3F	Female	Masking	hat	1527.73	-12.71	681.67	-21.89	69.83	110.47
S4M	Male	Masking	hat	1421.69	-12.45	816.94	-10.94	76.66	37.61
S5F	Female	Masking	hat	1852.75	7.78	861.19	-1.73	61.07	95.36
S6F	Female	Masking	hat	1668.56	-0.75	903.75	-3.32	74.32	89.48
Group Means Per Condition				1530.92	-3.81	750.20	-5.60	64.26	73.14

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First formant measurements were next examined. Computer simulation predicted that the bite block would result in a raising of F1 from the normal condition. The bar graphs on the right side of Figure 10.1 revealed that the adults with severe hearing loss displayed a raised F1, as predicted. The masking and the bite-block-plus-masking conditions also raised F1 in /i/ and /I/, but lowered it in /ae/.

Magnitude of Change

The left side of Figure 10.1 revealed that the adults with severe hearing loss exhibited moderate changes in F2 in test conditions compared to the normal condition, on the order of 8% or less. To determine whether any of the observed differences were statistically significant, a one-way, repeated measures analysis of variance by condition was performed for F2 for each vowel separately, equivalent to that done for the other subject groups. It was necessary to perform the repeated measures ANOVA on each vowel because there were missing data for S3F in the bite-block condition of hit and for all conditions of heat for S5F. (See Tables 10.1a and b.) A significant main effect of condition was found for every vowel. (See Table 10.2a.) Post hoc Least Significant Difference (LSD) comparisons showed that neither the bite-block condition nor the masking condition significantly lowered F2 in any vowel. (See Tables 10.3 a, b, and c.) However, for /ae/ F2, the masking condition lowered F2 and the bite block raised it, such that there was a significant difference between them (p=.03227). (See Table 10.3c.) The bite-block-plus-masking condition had the largest effect, significantly lowering F2 for the close vowels, /i/ and /I/. (See Tables 10.3 a and b.) In the case of /I/, the bite-block-plus-masking condition also was significantly different from the bite-block and the masking conditions, which had almost no effect. For /ae/, the bite-block-plus-masking condition was also significantly different from the bite-block condition (p=.01059) because the bite block raised F2, but the bite-block-plus-masking condition lowered it. (See Table 10.3c.)

The right side of Figure 10.1 showed that the adults with severe hearing loss exhibited slightly larger changes in F1 than in F2, on the order of 18% or less. A one-

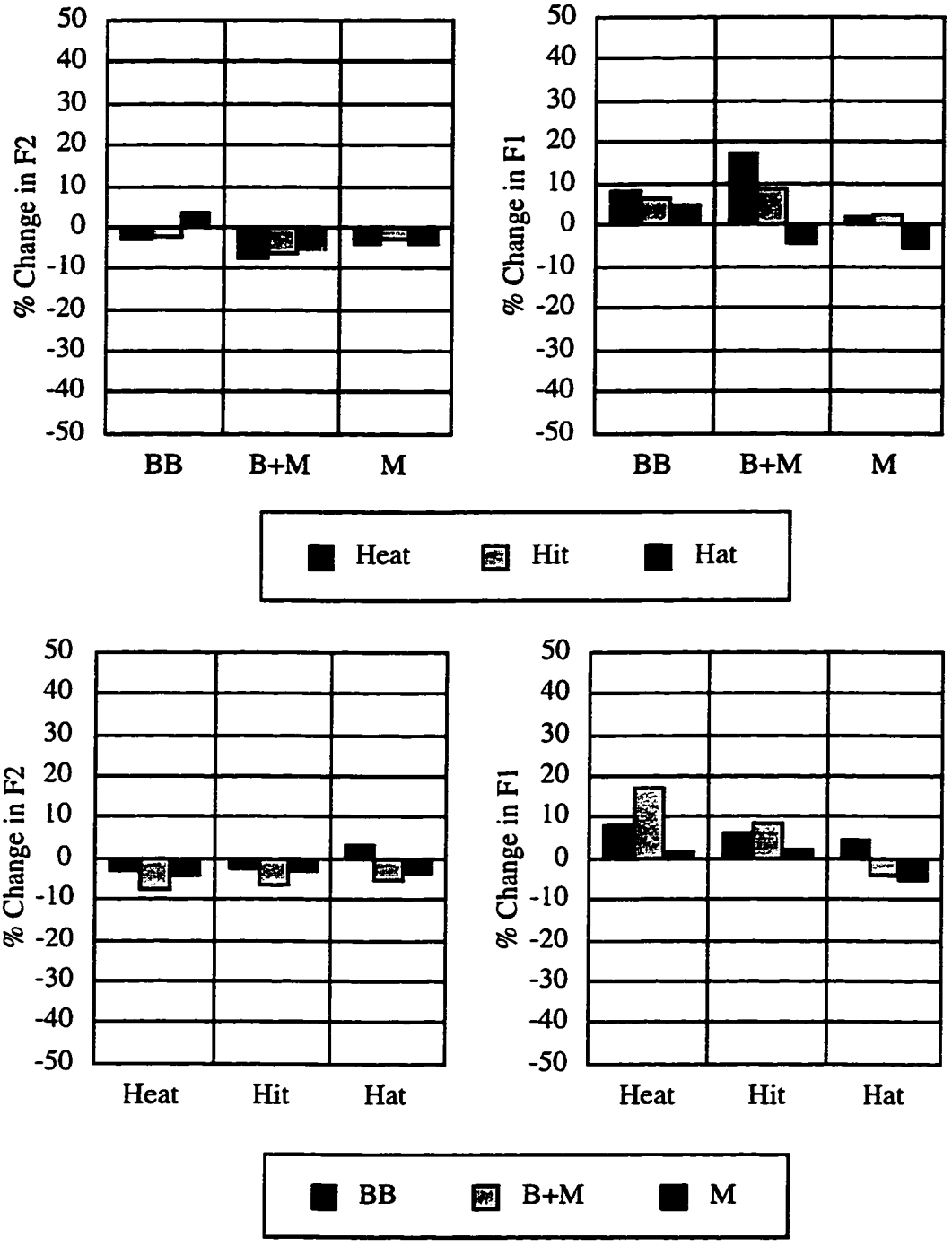
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way, repeated measures ANOVA, as described previously, was performed on individual mean F1 measurements for each vowel separately. (See Table 10.2b.) A significant main effect of condition was found for /i/ (p=.0027) and /ae/ (p=.0289). Post hoc LSD tests showed that neither the bite block nor masking significantly changed F1 in either vowel. (See Table 10.3 d and e.) However, for /ae/ F1, the masking condition lowered F1 and the bite block raised it, such that there was a significant difference between them (p=.00692). (See Table 10.3e.) Again, the bite-block-plus-masking condition had the largest effect, significantly raising /i/ F1. (See Table 10.3d.) In the case of /i/, the bite-block-plus-masking condition also was significantly different from the bite-block and the masking conditions, which had little effect. For /ae/, the bite-block-plus-masking condition was also significantly different from the bite-block condition (p=.01860) because the bite block raised F1, but the bite-block-plus-masking condition lowered it. (See Table 10.3e.)

The mean standard deviation in Hertz of F2 and F1 was next examined (Figure 10.2). If one compares Figures 7.2, 8.2, 9.2 and 10.2, it is apparent that F2 variability in the adults with profound and severe hearing loss was comparable. Both groups showed greater F2 variability than did adults with normal hearing, but less than did the children. Variability in F1, however, was comparable across all adult groups, but larger in the children. To determine if there were significant differences among conditions in terms of variability of production, one-way, repeated measures ANOVAs by condition, like those discussed previously, were performed on F2 and F1 standard deviations, but no significant effects of condition were found. (See Tables 10.2 c and d.)

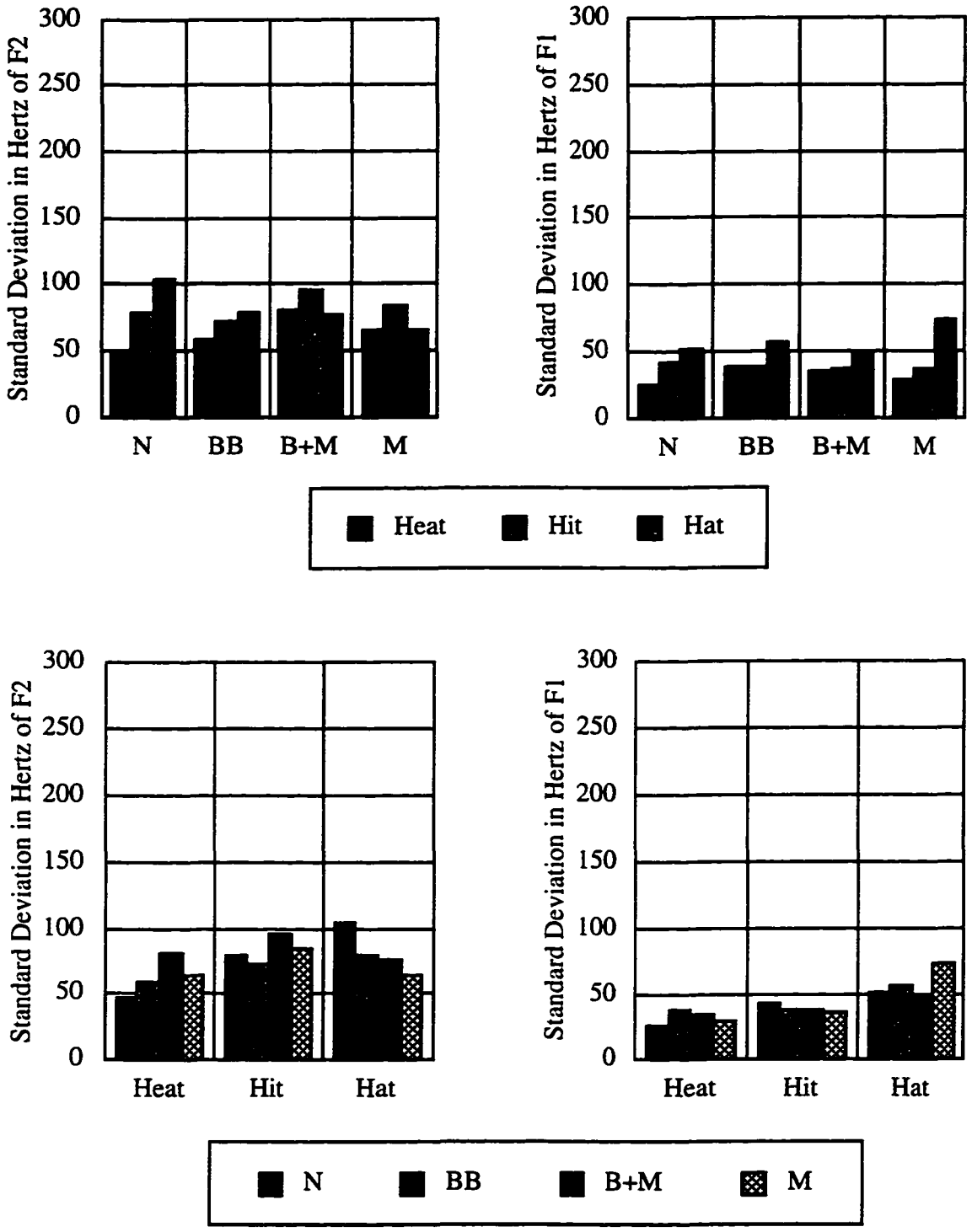
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Fig. 10.1. Mean % Change from Normal Condition in F2 and F1 in Bite-Block (BB), Bite-Block-Plus-Masking (B+M), and Masking (M) Conditions for Adults with Severe Hearing Loss



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Fig. 10.2. Mean Standard Deviation in Hertz of F2 and F1 in Bite-Block (BB), Bite-Block-Plus-Masking (B+M), and Masking (M) Conditions for Adults with Severe Hearing Loss



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Table 10.2a.--Repeated Measures One-Way Analysis of Variance: Mean F2 for Group of Adults with Severe Hearing Loss

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Heat					
Condition	75543.23	3	25181.08	3.66	.0441★
Error	82509.95	12	6875.83		
Hit					
Condition	69658.11	3	23219.37	5.51	.0130★
Error	50578.20	12	4214.85		
Hat					
Condition	76913.00	3	25637.66	3.39	.0457★
Error	113291.70	15	7552.78		

Table 10.2b.--Repeated Measures One-Way Analysis of Variance: Mean F1 for Group of Adults with Severe Hearing Loss

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Heat					
Condition	9019.74	3	3006.58	8.47	.0027★★
Error	4258.91	12	354.91		
Hit					
Condition	4972.89	3	1657.63	2.41	.1181
Error	8265.61	12	688.80		
Hat					
Condition	28093.19	3	9364.40	3.96	.0289★
Error	35435.64	15	2362.38		

Table 10.2c.--Repeated Measures One-Way Analysis of Variance: Mean Standard Deviation of F2 for Group of Adults with Severe Hearing Loss

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Heat					
Condition	2743.52	3	914.51	2.45	.1139
Error	4480.60	12	373.38		
Hit					
Condition	1802.14	3	600.71	.6175	.6168
Error	11673.39	12	972.78		
Hat					
Condition	4927.09	3	1642.36	.6280	.6080
Error	39227.34	15	2615.16		

★★ = $p<.01$, ★ = $p<.05$

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Table 10.2d.--Repeated Measures One-Way Analysis of Variance: Mean Standard Deviation of F1 for Group of Adults with Severe Hearing Loss

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Heat					
Condition	475.27	3	158.42	.97	.4405
Error	1967.86	12	163.99		
Hit					
Condition	284.03	3	94.68	.50	.6893
Error	2272.63	12	189.39		
Hat					
Condition	2001.40	3	667.13	2.03	.1526
Error	4923.95	15	328.26		

★★ = p<.01, ★ = p<.05

The tables of all post hoc test results follow.

Table 10.3a.--Summary of Results of Post Hoc Tests of the Main Effect of Condition on Heat F2 for Adults with Severe Hearing Loss

	Mean /i/ F2 in Four Conditions:		
N = 2191.65	BB = 2129.01	B+M = 2020.79	M = 2098.93

N v. BB	p = .25537
N v. B+M	p = .00685★★
N v. M	p = .10245
BB v. B+M	p = .06139
BB v. M	p = .57685
B+M v. M	p = .16206

Table 10.3b.--Summary of Results of Post Hoc Tests of the Main Effect of Condition on Hit F2 for Adults with Profound Hearing Loss

	Mean /I/ F2 in Four Conditions:		
N = 1894.05	BB = 1849.13	B+M = 1732.38	M = 1827.22

N v. BB	p = .29551
N v. B+M	p = .00197★★
N v. M	p = .12956
BB v. B+M	p = .01480★
BB v. M	p = .60323
B+M v. M	p = .03950★

★★ = p<.01, ★ = p<.05

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Table 10.3c.--Summary of Results of Post Hoc Tests of the Main Effect of Condition on Hat F2 for Adults with Severe Hearing Loss

Mean /ae/ F2 in Four Conditions:			
N = 1592.37	BB = 1649.32	B+M = 1502.88	M = 1530.92
	N v. BB	p = .27418	
	N v. B+M	p = .09474	
	N v. M	p = .23962	
	BB v. B+M	p = .01059★	
	BB v. M	p = .03227★	
	B+M v. M	p = .58443	

Table 10.3d.--Summary of Results of Post Hoc Tests of the Main Effect of Condition on Heat F1 for Adults with Severe Hearing Loss

Mean /i/ F1 in Four Conditions:			
N = 321.75	BB = 347.56	B+M = 376.20	M = 327.83
	N v. BB	p = .05119	
	N v. B+M	p = .00064★★	
	N v. M	p = .61956	
	BB v. B+M	p = .03330★	
	BB v. M	p = .12360	
	B+M v. M	p = .00158★★	

Table 10.3e.--Summary of Results of Post Hoc Tests of the Main Effect of Condition on Hat F1 for Adults with Severe Hearing Loss

Mean /ae/ F1 in Four Conditions:			
N = 801.33	BB = 837.95	B+M = 763.90	M = 750.20
	N v. BB	p = .21158	
	N v. B+M	p = .20210	
	N v. M	p = .08843	
	BB v. B+M	p = .01860★	
	BB v. M	p = .00692★★	
	B+M v. M	p = .63250	

★★ = $p<.01$, ★ = $p<.05$

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Summary

Tables 10.4 - 10.9 summarize the effects of all independent variables on all dependent variables for the group of adults with severe hearing loss and facilitate comparisons with the previous findings for the groups of adults and children with normal hearing and the adults with profound hearing loss. The reader is reminded that information from post hoc tests is provided only where a significant main effect of condition was obtained for a dependent variable.

The data from the group of adults with severe hearing loss revealed that:

A. The bite block condition lowered F2 in /i/ and /I/, but raised F2 in /ae/. (See Table 10.4.) The changes were small and not significant. The results for this group are more like the adults and the children with normal hearing in terms of direction of change, in that F2 in the close vowels was lowered, as predicted by computer simulation. However, just as with the adults with profound hearing loss, no significant effects of bite block on F2 were found. In contrast, the bite block lowered F2 significantly in heat for the adults with normal hearing and in all vowels for the children. The bite-block condition raised F1 in all vowels, as predicted by computer simulation for a greater-than-normal interincisal distance. The results for the adults with severe hearing loss mirror those of the adults with normal hearing in terms of direction of change, percent change, and the absence of significant changes in F1 as a result of bite block.

B. Masking resulted in small, non-significant changes in F2 and F1 (See Table 10.5.) It is not unexpected that subjects with severe, congenital hearing loss were not dramatically affected in production by removal of their hearing aids and presentation of 80-dB masking. However, it is noteworthy that there were small changes, nonetheless, and that they were largely in the same direction as those displayed by the adults with normal hearing, in contrast to the F2 raising pattern of the adults with profound hearing loss.

C. The bite-block-plus-masking condition resulted in significant F2 lowering for the close vowels, /i/ and /I/. (See Table 10.6.) The direction of change was the same as that

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exhibited by the groups with normal hearing, but this condition affected both high vowels in the severely hearing-impaired, whereas the adults with normal hearing experienced significant changes for /i/ only. (The children had exhibited significant F2 changes in all vowels.) This group contrasted quite dramatically with the adults with profound hearing loss, both in direction and magnitude of change. For F1, the results were similar to those for the adults and the children with normal hearing in terms of percent change. Like the children, the adults with severe hearing loss lowered /ae/ F1. The adults with severe hearing loss and the adults and the children with normal hearing each showed a significant change in F1 for one vowel; the affected vowel was /i/, /I/ and /ae/, respectively. The only group that showed no significant F1 changes in the bite-block-plus-masking condition was the adults with profound hearing loss.

D. Test conditions did not result in significant changes in F2 or F1 variability. (Tables 10.7 - 10.9.) These results are in contrast to the increased /ae/ F2 variability seen in the adults with normal hearing as a result of bite block, and to the increased /i/ and /ae/ F1 variability seen in the two conditions employing a bite block for the adults with profound hearing loss.

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Table 10.4.--Summary of Bite-Block Effects on F2 and F1 for Groups of Subjects

	Adults with Normal Hearing	Children with Normal Hearing	Adults with Profound Hearing Loss	Adults with Severe Hearing Loss
F2 Direction of Change:				
heat	lowered	lowered	lowered	lowered
hit	lowered	lowered	raised	lowered
hat	lowered	lowered	lowered	raised
% Change	<3%	<11%	<3%	<4%
Post Hoc Tests of Main Effect of Condition for Heat:				
N v. BB	↓ ★	↓ ★★		
Hit:				
N v. BB		↓ ★		
Hat:				
N v. BB		↓ ★★		
F1 Direction of Change:				
heat	raised	raised	raised	raised
hit	raised	raised	lowered	raised
hat	raised	lowered	lowered	raised
% Change	<8%	<20%	<4%	< or = 8%
Post Hoc Tests of Main Effect of Condition for Heat:				
N v. BB				
Hit:				
N v. BB				
Hat:				
N v. BB		↓ ★★		

★★=p<.01, ★=p<.05, ↑ = raised formant, ↓ = lowered formant

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Table 10.5.--Summary of Masking Effects on F2 and F1 for Groups of Subjects

	Adults with Normal Hearing	Children with Normal Hearing	Adults with Profound Hearing Loss	Adults with Severe Hearing Loss
F2 Direction of Change:				
heat	lowered	lowered	raised	lowered
hit	lowered	raised	raised	lowered
hat	lowered	lowered	raised	lowered
% Change	<4%	<2%	<4%	<5%
Post Hoc Tests of Main Effect of Condition for Heat:				
N v. M	↓ ★			
BB v. M		★★		
Hit:				
N v. M				
BB v. M		★★		
Hat:				
N v. M				
BB v. M		★		★
F1 Direction of Change:				
heat	raised	raised	raised	raised
hit	raised	raised	lowered	raised
hat	raised	raised	lowered	lowered
% Change	<12%	<15%	<3%	<6%
Post Hoc Tests of Main Effect of Condition for Heat:				
N v. M				
BB v. M				
Hit:				
N v. M				
BB v. M				
Hat:				
N v. M				
BB v. M		★★		★★

★★=p<.01, ★=p<.05, ↑ = raised formant, ↓ = lowered formant

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Table 10.6.--Summary of Bite-Block-Plus-Masking Effects on F2 and F1 for Groups of Subjects

	Adults with Normal Hearing	Children with Normal Hearing	Adults with Profound Hearing Loss	Adults with Severe Hearing Loss
F2 Direction of Change:				
heat	lowered	lowered	raised	lowered
hit	lowered	lowered	raised	lowered
hat	lowered	lowered	lowered	lowered
% Change	<7%	<10%	<3%	<8%
Post Hoc Tests of Main Effect of Condition for Heat:				
N v. BM	↓ ★★	↓ ★★		↓ ★★
BB v. B+M	★★			
M v. B+M	★★	★★		
Hit:				
N v. BM		↓ ★		↓ ★★
BB v. B+M				★
M v. B+M		★★		★
Hat:				
N v. BM	↓ ★★	↓ ★		
BB v. B+M				★
M v. B+M				
F1 Direction of Change:				
heat	raised	raised	raised	raised
hit	raised	raised	raised	raised
hat	raised	lowered	unchanged	lowered
% Change	<17%	<15%	<7%	<18%
Post Hoc Tests of Main Effect of Condition for Heat:				
N v. BM				↑ ★★
BB v. B+M				★
M v. B+M				★★
Hit:				
N v. BM	↑ ★★			
BB v. B+M	★★			
M v. B+M				
Hat:				
N v. BM		↓ ★		
BB v. B+M				★
M v. B+M		★★		

★★=p<.01, ★=p<.05, ↑ = raised formant, ↓ = lowered formant

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Table 10.7.--Summary of Bite-Block Effects on F2SD and F1SD for Groups of Subjects

	Adults with Normal Hearing	Children with Normal Hearing	Adults with Profound Hearing Loss	Adults with Severe Hearing Loss
Post Hoc Tests of Main Effect of Condition for Heat F2SD: N v. BB				
Hit F2SD: N v. BB				
Hat F2SD: N v. BB	↑ ★★			
Post Hoc Tests of Main Effect of Condition for Heat F1SD: N v. BB			↑ ★[1]	
Hit F1SD: N v. BB				
Hat F1SD: N v. BB			↑ ★[2]	

★★=p<.01, ★=p<.05, ↑ = increased variability, ↓ = decreased variability

[1] Post hoc test conducted of a main effect of condition for heat F1 standard deviation of p=.0591.
[2] Post hoc test conducted of a main effect of condition for hat F1 standard deviation of p=.0525.

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Table 10.8.--Summary of Masking Effects on F2SD and F1SD for Groups of Subjects

	Adults with Normal Hearing	Children with Normal Hearing	Adults with Profound Hearing Loss	Adults with Severe Hearing Loss
Post Hoc Tests of Main Effect of Condition for Heat F2SD:				
N v. M				
BB v. M				
Hit F2SD:				
N v. M				
BB v. M				
Hat F2SD:				
N v. M				
BB v. M	★	★		
Post Hoc Tests of Main Effect of Condition for Heat F1SD:				
N v. M				
BB v. M				
Hit F1SD:				
N v. M				
BB v. M				
Hat F1SD:				
N v. M				
BB v. M			★★	

★★=p<.01, ★=p<.05, ↑ = increased variability, ↓ = decreased variability

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Table 10.9--Summary of Bite-Block-Plus-Masking Effects on F2SD and F1SD for Groups of Subjects

	Adults with Normal Hearing	Children with Normal Hearing	Adults with Profound Hearing Loss	Adults with Severe Hearing Loss
Post Hoc Tests of Main Effect of Condition for Heat F2SD:				
N v. B+M				
BB v. B+M				
M v. B+M				
Hit F2SD:				
N v. B+M				
BB v. B+M				
M v. B+M				
Hat F2SD:				
N v. B+M				
BB v. B+M	★★			
M v. B+M		★		
Post Hoc Tests of Main Effect of Condition for Heat F1SD:				
N v. B+M				
BB v. B+M				
M v. B+M			★	
Hit F1SD:				
N v. B+M				
BB v. B+M				
M v. B+M				
Hat F1SD:				
N v. B+M			↑ ★[3]	
BB v. B+M				
M v. B+M			★★	

★★=p<.01, ★=p<.05, ↑ = increased variability, ↓ = decreased variability

[3] Post hoc test conducted of a main effect of condition for hat F1 standard deviation of p=.0525.

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Individual Data

To discover the distinctive patterns of compensatory adjustments made by individuals in response to test conditions, the data from each adult with severe hearing loss were examined separately. (See Tables 10.10 - 10.15 and Figures 10.3 - 10.9.)

Direction of Change

F2

The bite block lowered /i/ and /ɪ/ F2 from the normal condition in a majority of the subjects. The pattern was consistent with predictions from computer simulation. However, /ae/ F2 showed a pattern of raising in a majority of the individuals. A special note must be made about the data from S3F. (See Figure 10.5.) While all the other subjects with severe hearing loss displayed a pattern of F2 lowering for /i/, she showed a pattern of F2 raising. S3F had the greatest average hearing loss (92dB) and the second lowest word intelligibility score among the subjects with severe hearing loss. (See Figure 6.1 in Chapter Six.) Given her hearing loss and the pattern of her /i/ F2 results, it is of interest to recall the general pattern of F2 raising displayed by the adults with profound hearing loss, discussed in the last chapter. Unfortunately, her data were missing for /ɪ/ in the bite-block condition. Ironically, all of the other subjects except S4M showed a pattern of lowering /ɪ/ F2 in the bite-block condition, but he had the least average hearing loss (63 dB) in the severely hearing-impaired group and the second best word intelligibility score. (Again, see Figure 6.1 in Chapter Six.)

The bite-block-plus-masking condition lowered F2 from the normal condition for every vowel in every subject except S3F. In fact, once again, S3F was the only subject who raised F2 for the close vowels /i/ and /ɪ/. (See Figure 10.5.)

The masking condition also lowered F2 across vowels in most of the speakers. Again, for the vowel /ɪ/, S3F was the only speaker who raised F2. (See Figure 10.5.)

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F1

The bite block resulted in a raising of F1 for heat and hit. This pattern of change was consistent with predictions from computer simulation. However, there was no clear direction of change in hat F1. It was lowered as often as it was raised.

The bite-block-plus-masking condition raised /i/ and /I/ F1, but lowered F1 in /ae/ for most of the subjects.

Masking raised F1 in heat and hit, but lowered it in hat. Overall, these changes mirrored those in the other two conditions.

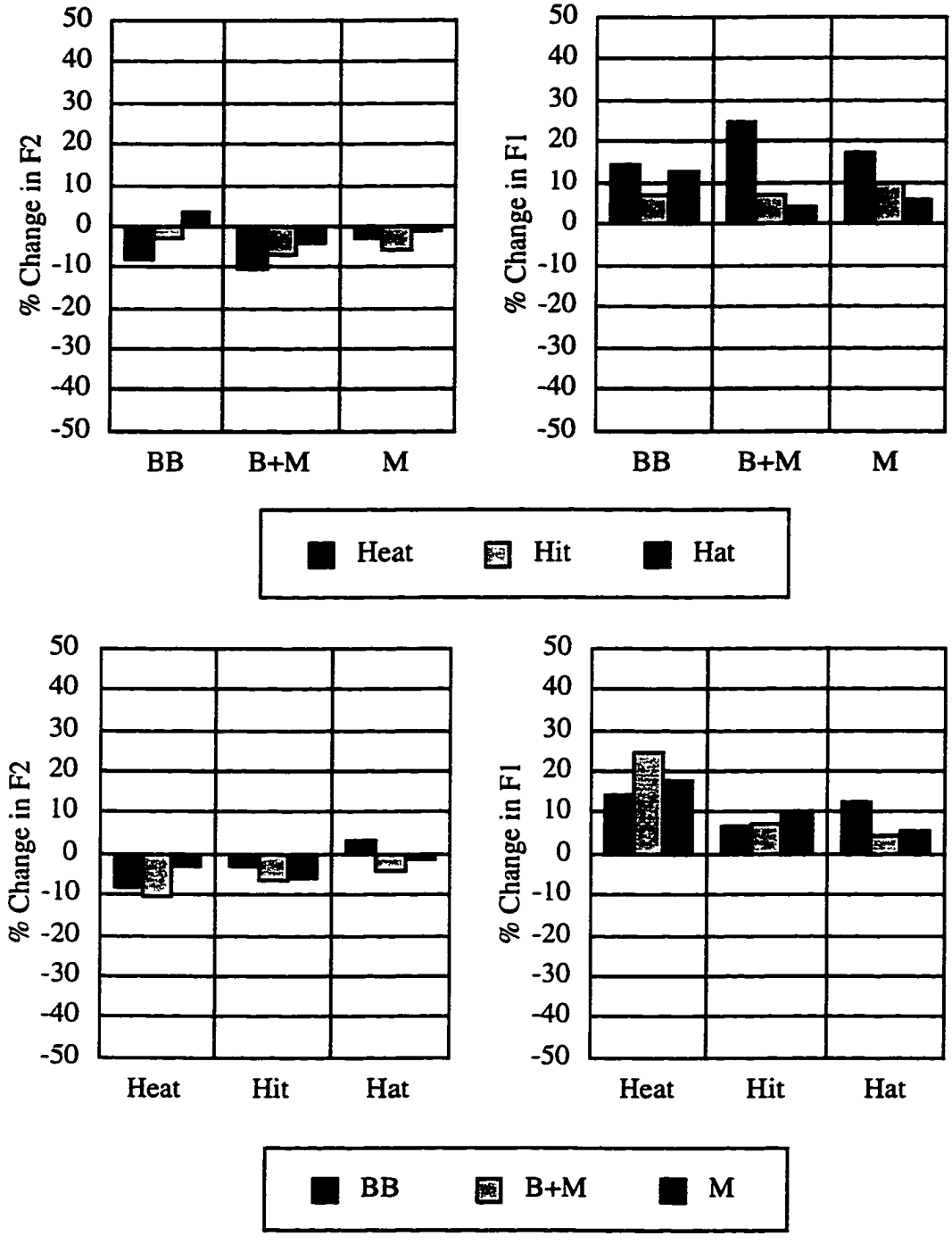
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Table 10.10.--Subject S1M: Means, Standard Deviations and Percent Change in Formants from Normal Condition to Test Conditions

Vowel	Condition	N	Mean F2	% Ch F2	Mean F1	% Ch F1	F2 St Dev	F1 St Dev
Heat	Normal	13	2052.31	***	310.85	***	46.27	10.71
	Bite Block	16	1884.56	-8.17	355.38	14.33	39.45	37.81
	Bite Block and Masking	15	1842.60	-10.22	387.67	24.71	69.90	16.67
	Masking	13	1986.54	-3.20	364.92	17.39	73.53	25.62
Hit	Normal	16	1612.69	***	447.69	***	64.20	28.59
	Bite Block	16	1563.25	-3.07	478.81	6.95	53.33	48.25
	Bite Block and Masking	16	1504.88	-6.69	479.38	7.08	79.18	42.13
	Masking	16	1520.69	-5.70	492.31	9.97	40.78	47.65
Hat	Normal	16	1420.81	***	670.63	***	36.22	52.71
	Bite Block	15	1471.33	3.56	754.67	12.53	57.78	74.42
	Bite Block and Masking	16	1361.25	-4.19	699.63	4.32	69.37	49.78
	Masking	16	1401.81	-1.34	708.44	5.64	46.52	39.75

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Fig. 10.3. % Change from Normal Condition in F2 and F1 in Bite-Block (BB), Bite-Block-Plus-Masking (B+M), and Masking (M) Conditions for Subject S1M



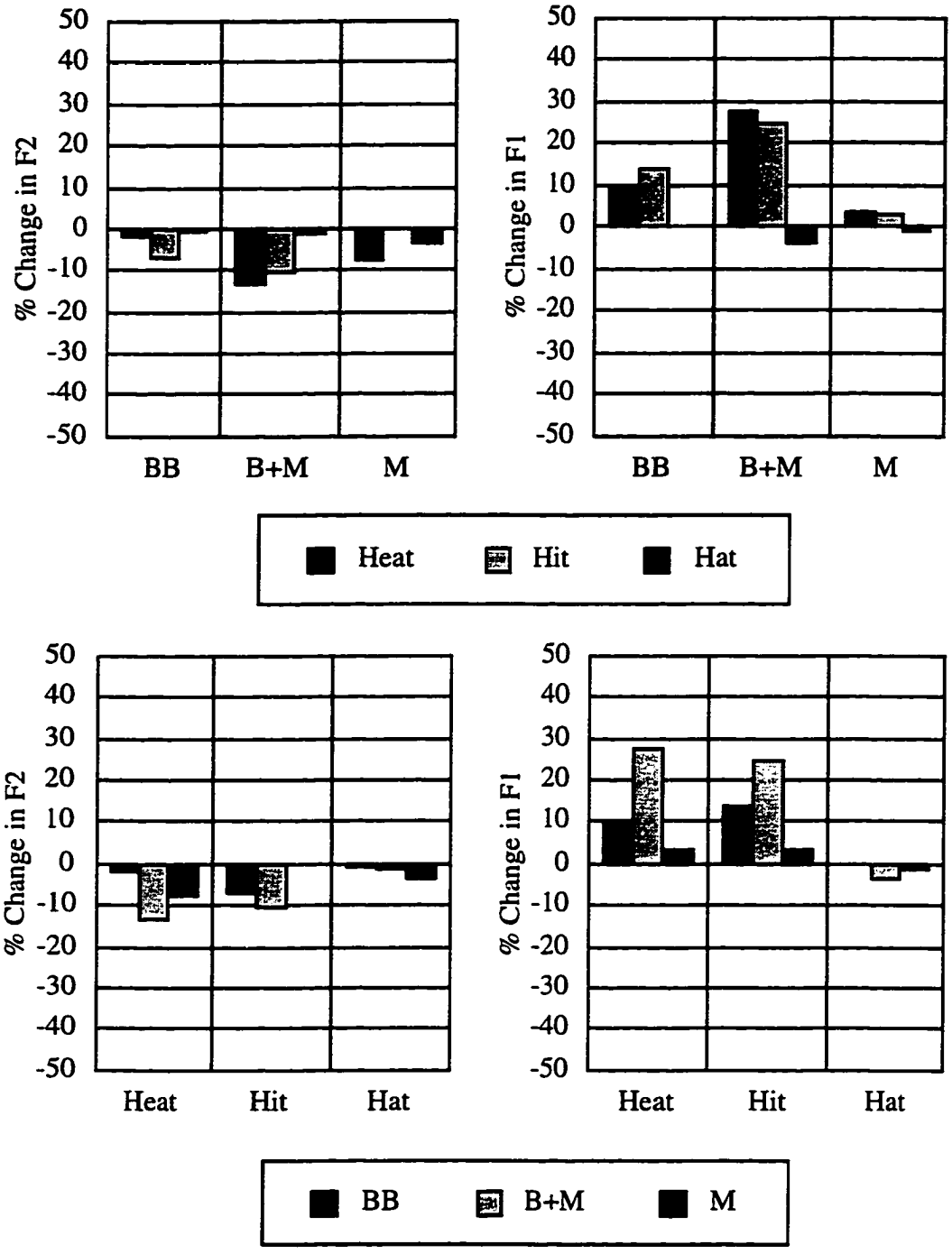
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Table 10.11.--Subject S2M: Means, Standard Deviations and Percent Change in Formants from Normal Condition to Test Conditions

Vowel	Condition	N	Mean F2	% Ch F2	Mean F1	% Ch F1	F2 St Dev	F1 St Dev
Heat	Normal	15	1994.20	***	270.80	***	51.68	26.67
	Bite Block	16	1963.13	-1.56	297.38	9.82	64.86	18.59
	Bite Block and Masking	16	1724.00	-13.55	345.13	27.45	124.22	35.98
	Masking	17	1843.35	-7.56	279.77	3.31	51.62	18.60
Hit	Normal	16	1639.69	***	350.19	***	112.43	45.37
	Bite Block	16	1526.81	-6.88	398.13	13.69	89.36	52.94
	Bite Block and Masking	15	1468.93	-10.41	436.00	24.50	69.29	44.75
	Masking	16	1638.63	-0.06	360.81	3.03	128.96	40.72
Hat	Normal	16	1359.06	***	536.38	***	63.95	38.49
	Bite Block	16	1352.00	-0.52	535.38	-0.19	40.63	61.04
	Bite Block and Masking	16	1345.38	-1.01	516.00	-3.80	44.89	30.17
	Masking	15	1313.00	-3.39	529.20	-1.34	57.17	66.16

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Fig. 10.4. % Change from Normal Condition in F2 and F1 for Subject S2M



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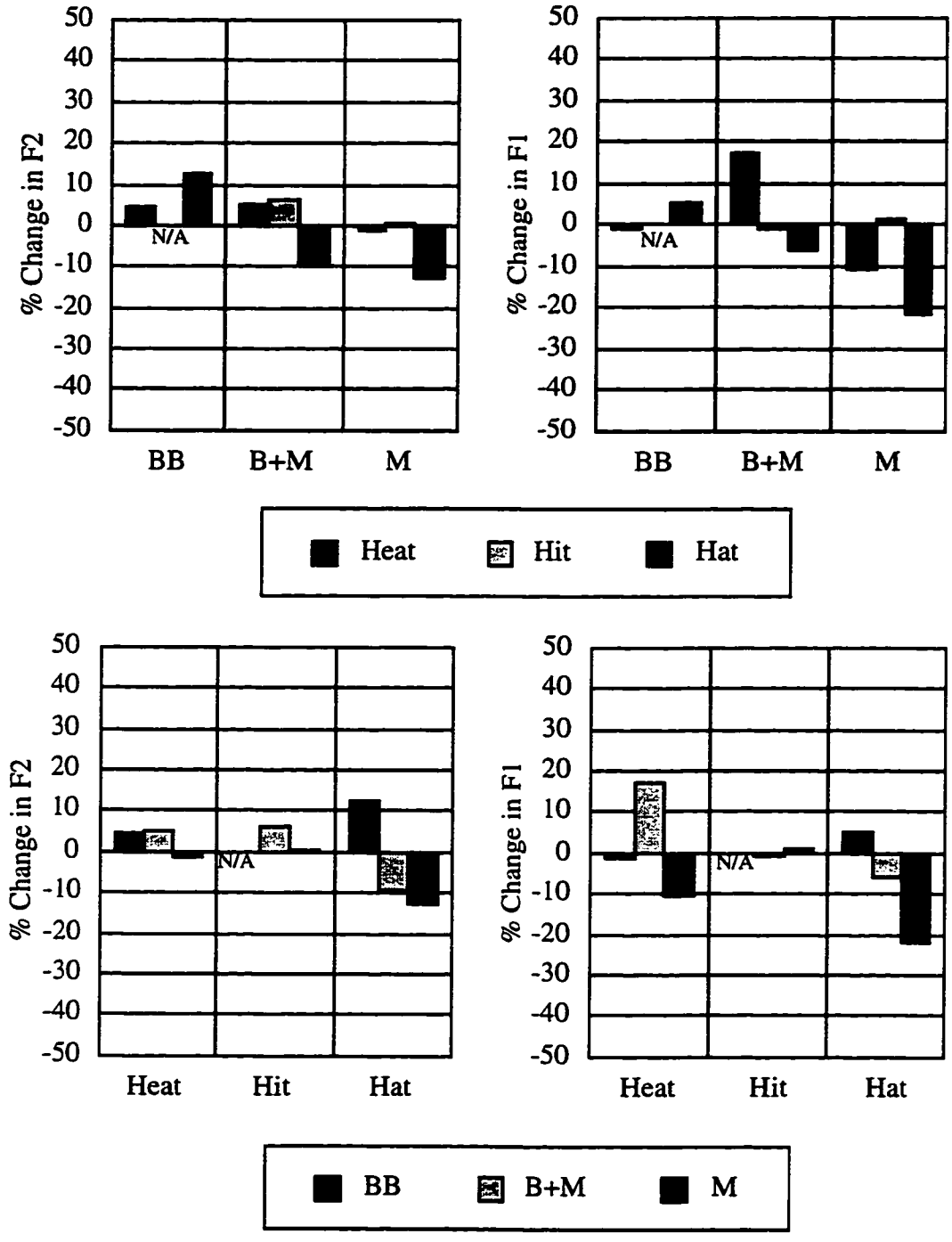
Table 10.12.--Subject S3F: Means, Standard Deviations and Percent Change in Formants from Normal Condition to Test Conditions

Vowel	Condition	N	Mean F2	% Ch F2	Mean F1	% Ch F1	F2 St Dev	F1 St Dev
Heat	Normal	11	2127.91	***	321.27	***	66.22	50.13
	Bite Block	12	2227.25	4.67	317.83	-1.07	58.47	49.65
	Bite Block and Masking	14	2237.00	5.13	376.93	17.32	66.76	42.64
	Masking	14	2096.29	-1.49	286.71	-10.76	57.72	20.36
Hit	Normal	9	1970.11	***	420.89	***	79.38	24.18
	Bite Block	7[4]	N/A	N/A	N/A	N/A	N/A	N/A
	Bite Block and Masking	8	2094.88	6.33	416.75	-0.98	109.15	37.60
	Masking	10	1977.10	0.35	425.60	1.12	160.63	31.94
Hat	Normal	15	1750.20	***	872.67	***	81.05	50.07
	Bite Block	16	1974.13	12.79	916.94	5.07	64.14	50.19
	Bite Block and Masking	16	1592.69	-9.00	818.56	-6.20	117.83	59.33
	Masking	15	1527.73	-12.71	681.67	-21.89	69.83	110.47
Hat[5]	Normal	14			358.14	***		59.09
	Bite Block	14			407.79	13.86		51.14
	Bite Block and Masking	5			388.60	8.51		52.19
	Masking	1			380.00	6.10		N/A

[4] Criterion for the inclusion of a condition was a minimum of eight tokens for which both F2 and F1 measurements were obtained. Bandwidths over which many of the F1 values were resolved were narrower than 50 Hz. Those tokens were removed, leaving only seven tokens for this vowel in this condition.
[5] Subject S3F exhibited a noticeably harsh voice quality during /ae/ vowel production. In several tokens a low resonance was detected by LPC analysis, not typical of F1 or F2 for /ae/. It appeared below the other evident peaks in the frequency range typically associated with /ae/. It may have resulted from a tracheal resonance. The values are included here for the reader's information, but were not used in figures or statistical analyses.

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Fig. 10.5. % Change from Normal Condition in F2 and F1 in Bite-Block (BB), Bite-Block-Plus-Masking (B+M), and Masking (M) Conditions for Subject S3F



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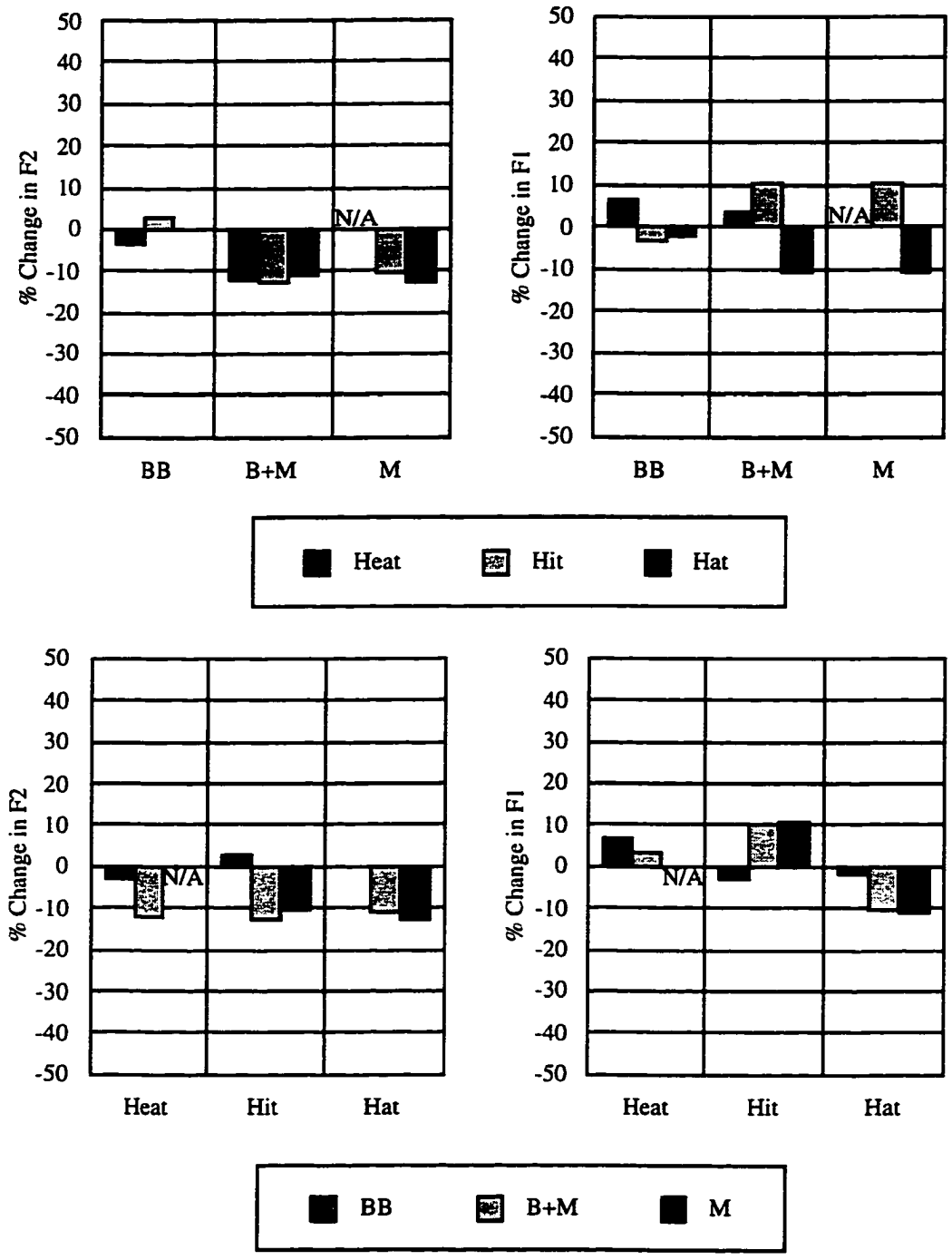
Table 10.13.--Subject S4M: Means, Standard Deviations and Percent Change in Formants from Normal Condition to Test Conditions

Vowel	Condition	N	Mean F2	% Ch F2	Mean F1	% Ch F1	F2 St Dev	F1 St Dev
Heat	Normal	13	2325.54	***	311.92	***	44.44	22.86
	Bite Block	10	2250.10	-3.24	332.40	6.57	56.21	25.38
	Bite Block and Masking	8	2038.00	-12.36	322.25	3.31	90.57	19.33
	Masking	5[6]	N/A	N/A	N/A	N/A	N/A	N/A
Hit	Normal	14	1913.64	***	475.29	***	74.83	33.96
	Bite Block	16	1971.00	3.00	460.44	-3.12	56.18	30.17
	Bite Block and Masking	14	1664.79	-13.00	523.57	10.16	79.00	38.66
	Masking	14	1719.00	-10.17	525.14	10.49	64.09	31.68
Hat	Normal	16	1623.94	***	917.25	***	61.03	51.78
	Bite Block	15	1621.73	-0.14	898.33	-2.06	138.01	44.81
	Bite Block and Masking	16	1444.25	-11.07	819.81	-10.62	51.15	43.22
	Masking	16	1421.69	-12.45	816.94	-10.94	76.66	37.61

[6] Criterion for the inclusion of a condition was a minimum of eight tokens for which both F2 and F1 measurements were obtained. Bandwidths over which many of the F1 values were resolved were narrower than 50 Hz. Those tokens were removed, leaving only five tokens for this vowel in this condition.

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Fig. 10.6. % Change from Normal Condition in F2 and F1 in Bite-Block (BB), Bite-Block-Plus-Masking (B+M), and Masking (M) Conditions for Subject S4M



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Table 10.14.--Subject S5F: Means, Standard Deviations and Percent Change in Formants from Normal Condition to Test Conditions

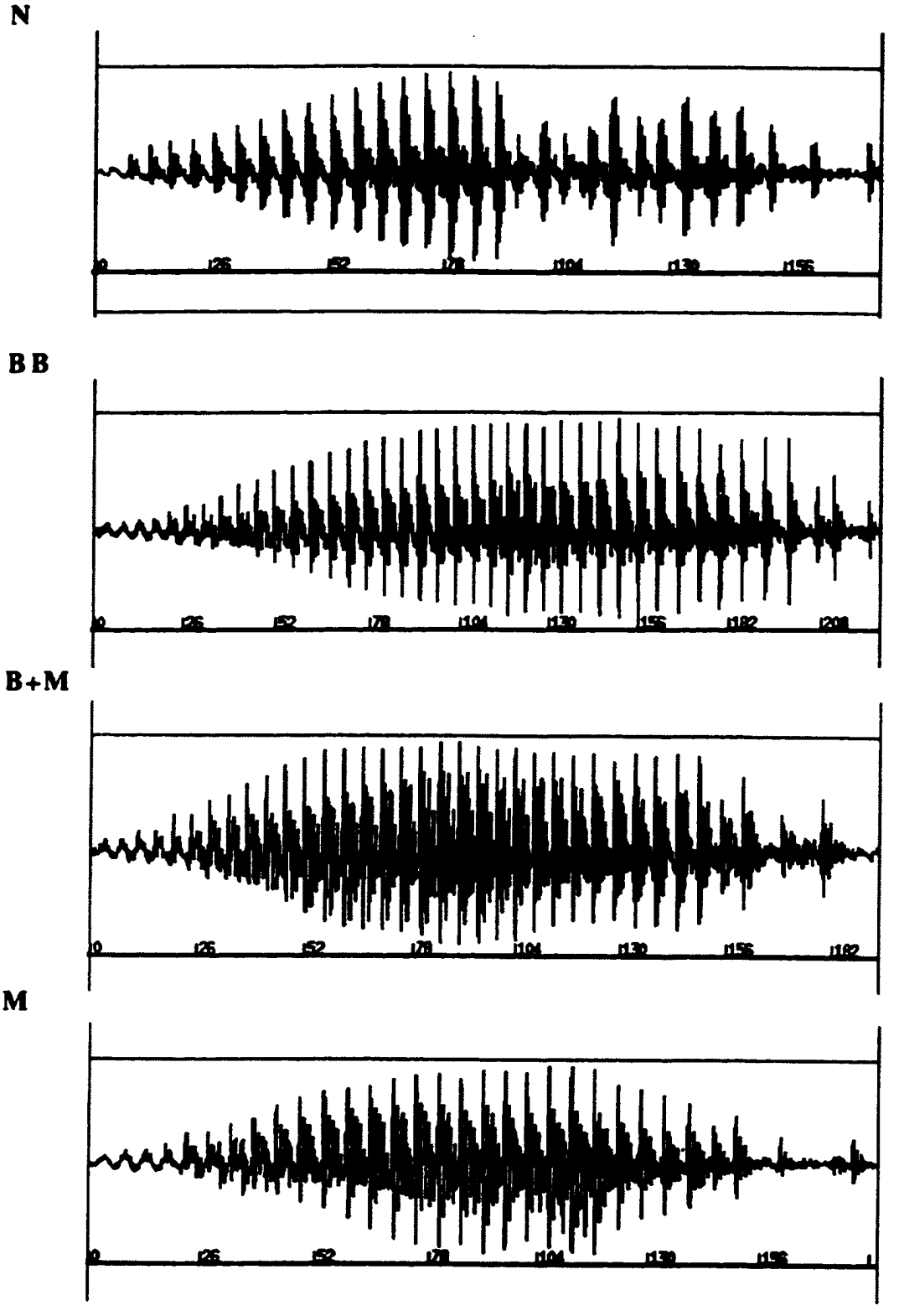
Vowel	Condition	N	Mean F2	% Ch F2	Mean F1	% Ch F1	F2 St Dev	F1 St Dev
Heat[7]	Normal	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Bite Block	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Bite Block and Masking	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Masking	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Hit	Normal	15	2081.40	***	465.53	***	57.27	32.59
	Bite Block	13	2068.54	-0.62	516.39	10.93	92.36	28.12
	Bite Block and Masking	14	1965.29	-5.58	486.71	4.55	175.21	20.82
	Masking	8	2058.13	-1.12	447.00	-3.98	47.81	22.89
Hat	Normal[8]	16	1719.00	***	876.31	***	92.29	62.33
	Bite Block	14	1749.21	1.76	1010.50	15.31	102.68	74.11
	Bite Block and Masking	16	1712.94	-0.35	826.69	-5.66	109.33	85.18
	Masking	16	1852.75	7.78	861.19	-1.73	61.07	95.36
Hat	Normal		1262.19	0.00	876.31	***	80.20	62.33
	Bite Block		N/A	38.59	1010.50	15.31	N/A	74.11
	Bite Block and Masking		N/A	35.71	826.69	-5.66	N/A	85.18
	Masking		N/A	46.79	861.19	-1.73	N/A	95.36

[7] Criterion for the inclusion of a condition was a minimum of eight tokens for which both F2 and F1 measurements were obtained. This vowel was extremely problematic. F1 bandwidths were so very narrow as to be virtually unusable in nearly every case. F0 seemed to completely dominate the region where F1 should have been detected. The removal of tokens where F1 was resolved over bandwidths narrower than 50 Hz resulted in a failure to obtain the minimum eight tokens in any condition for this vowel.

[8] Voice quality in this condition was harsh and nasal. The tokens from the normal condition were different from those in the test conditions in three ways. First, LPC cross sections revealed four resonance peaks in the normal condition only. The second resonance peak was believed to be nasal or tracheal. The values are provided in the bottom block of this table for the information of the reader, presented as if this second resonance peak were to be taken as F2. These values were not used, however, in figures or statistical analyses. Because of it, LPC analysis could not detect the true first formant, clearly visible by eye, but greatly reduced in amplitude. The nasal resonance or the harsh voice quality may have resulted in reduced energy in the F1 region. Second, the waveforms in the normal condition looked dramatically different from the waveforms in the other conditions. (See Figure 10.7.) Third, the tokens also sounded dramatically different from the tokens in the test conditions. Consequently, Hades DFT measures were used for the entire normal /ae/ condition, because no accurate measures could be obtained from LPC analysis. This is the only instance in this dissertation in which DFT measures were used rather than LPC-derived values.

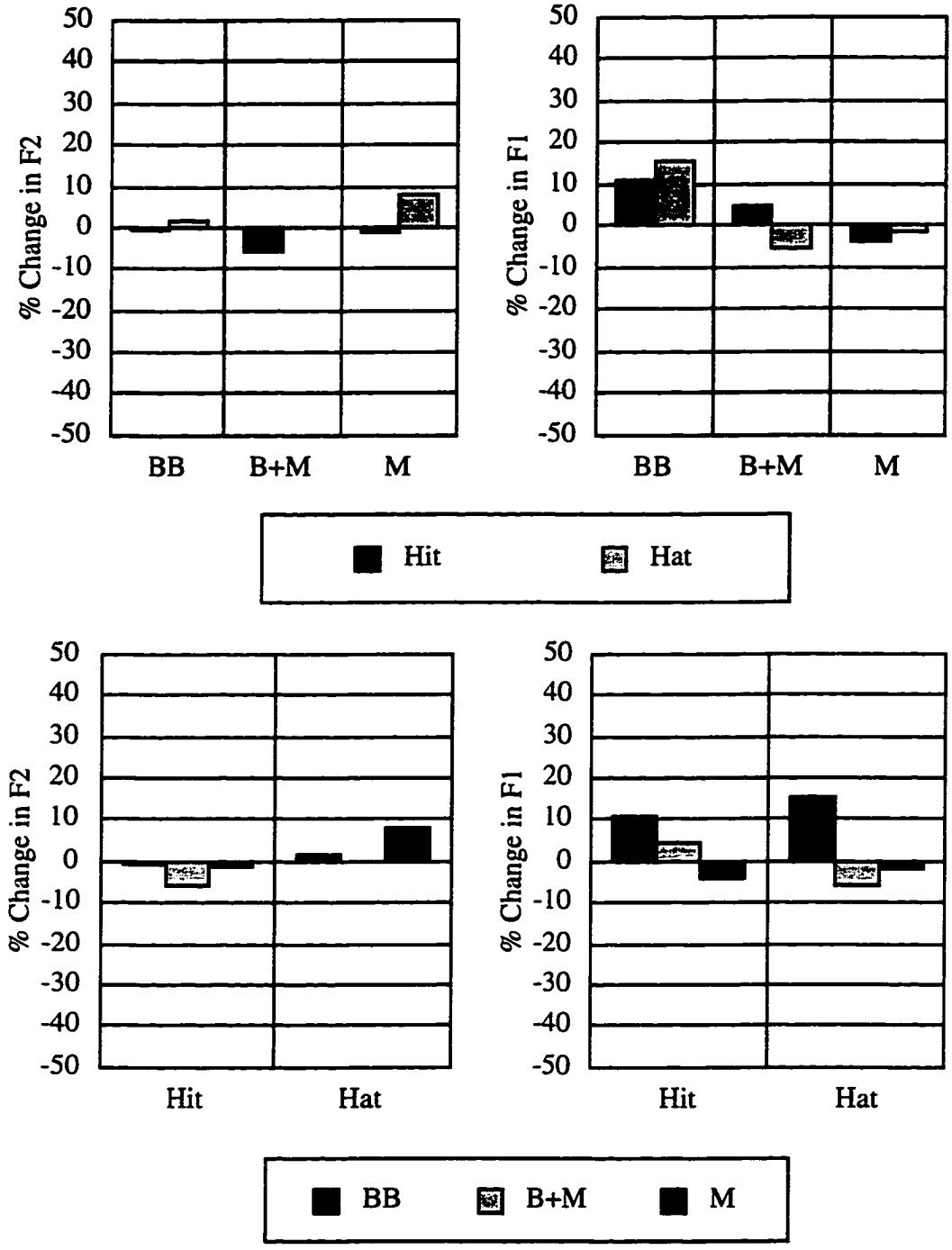
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Fig. 10.7. Waveforms of Subject S5F in the Four Conditions of /ae/



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Fig. 10.8. % Change from Normal Condition in F2 and F1 in Bite-Block (BB), Bite-Block-Plus-Masking (B+M), and Masking (M) Conditions for Subject S5F



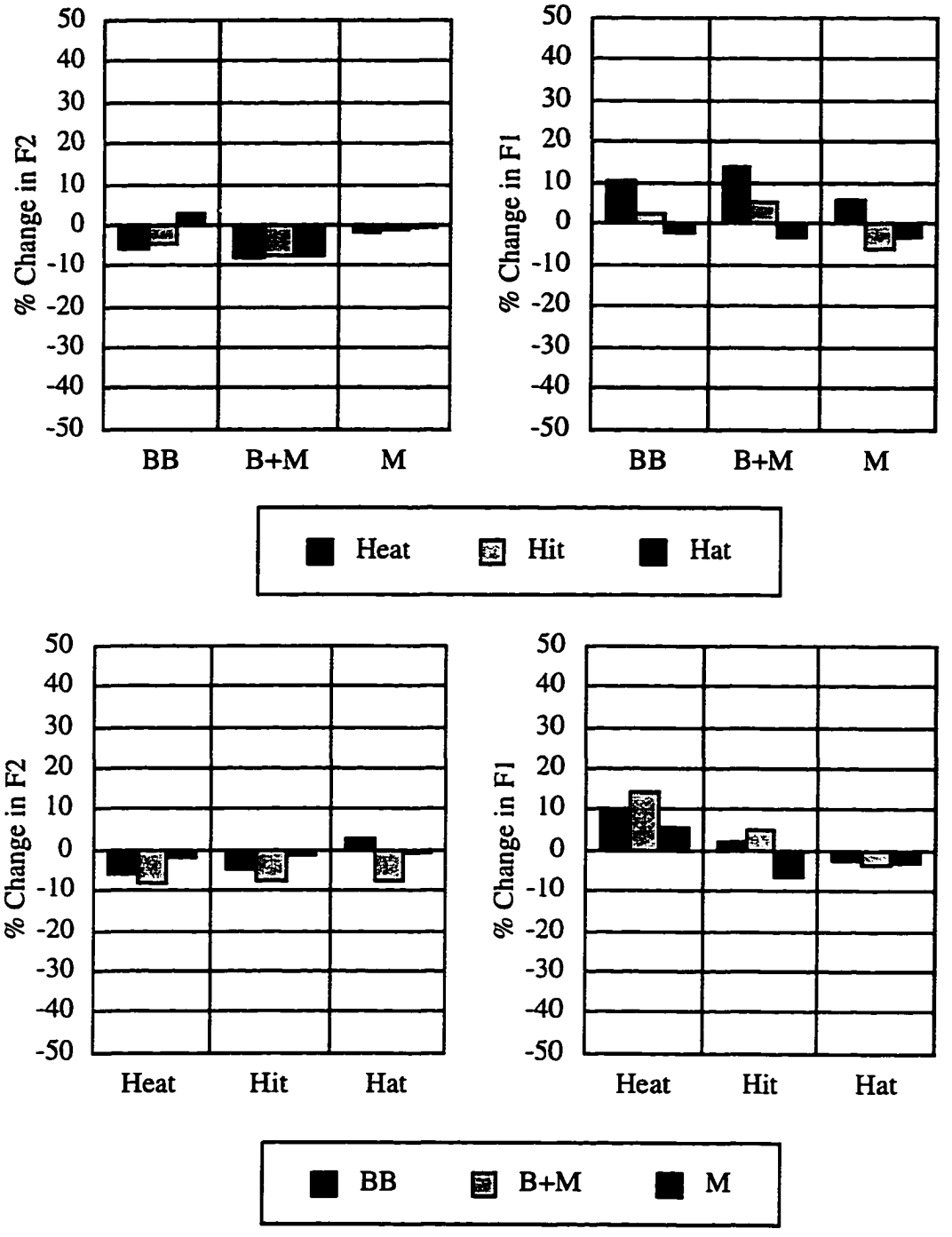
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Table 10.15.--Subject S6F: Means, Standard Deviations and Percent Change in Formants from Normal Condition to Test Conditions

Vowel	Condition	N	Mean F2	% Ch F2	Mean F1	% Ch F1	F2 St Dev	F1 St Dev
Heat	Normal	14	2458.29	***	393.93	***	28.97	17.81
	Bite Block	15	2320.00	-5.63	434.80	10.37	76.88	58.00
	Bite Block and Masking	14	2262.36	-7.97	449.00	13.98	49.08	60.09
	Masking	14	2414.86	-1.77	416.93	5.84	52.66	45.64
Hit	Normal	16	2222.81	***	480.56	***	82.63	90.28
	Bite Block	15	2116.07	-4.80	490.60	2.09	69.37	32.67
	Bite Block and Masking	16	2058.00	-7.41	504.38	4.96	65.41	37.58
	Masking	16	2199.63	-1.04	449.50	-6.46	63.06	44.37
Hat	Normal	16	1681.19	***	934.75	***	287.51	54.62
	Bite Block	16	1727.50	2.75	911.88	-2.45	71.45	31.92
	Bite Block and Masking	16	1555.75	-7.46	902.69	-3.43	64.37	33.53
	Masking	16	1668.56	-0.75	903.75	-3.32	74.32	89.48

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Fig. 10.9. % Change from Normal Condition in F2 and F1 in Bite-Block (BB), Bite-Block-Plus-Masking (B+M), and Masking (M) Conditions for Subject S6F



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Magnitude of Change

To determine whether observed changes were statistically significant, three-way ANOVAs (Bite Block x Masking x Vowel) were performed for F2 and F1 for each adult with severe hearing loss, treating each token from each condition as one sample, just as had been done with the other individual subjects. One adult with severe hearing loss, S5F, was missing data for all conditions of the vowel /i/. For her, comparisons were made with two vowels rather than three. Two-way ANOVAs, also identical to those performed for the other individual subjects, were performed on the standard deviation values of F2 and F1 for each subject separately, using the twelve standard deviation values from three vowels in four conditions as the raw data. Three-way ANOVAs could not be performed because each cell had only one value. Thus the analyses were collapsed across one dimension, to perform two-way ANOVAs (BB x M; BB x V; and M x V). Two subjects, S3F and S4M, each were missing data for one test condition for one vowel. Missing cells made two-way and three-way ANOVAs impossible to use for those vowels. They were removed and analyzed by one-way ANOVAs for Condition, using data from the conditions that remained. Those special F tables may be found in Appendices F3e-f and F4e-f. All other F tables for all the reported results that follow may be found for each adult with severe hearing loss (S1-S6) as Appendices F1 - F6, respectively.

F2

Table 10.16 summarizes the statistically significant changes in F2 frequency and F2 variability found for each individual adult with severe hearing loss.

A significant ($p<.01$) main effect of bite block on F2 was revealed for five of six of the adults with severe hearing loss. For four individuals, F2 was lowered. Further evidence was provided from the individual analysis of the vowel /i/ for S4M. (See Appendix F4e.) A significant ($p=.00000$) effect of Condition on F2 was found.

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Subsequent Post Hoc HSD tests for unequal sample sizes revealed that the bite-block condition was significantly (p=.03066) lowered from the normal condition.

A significant (p<.01) main effect of masking on F2 was shown for five of the six adults with severe hearing loss. In all cases, F2 was lowered.

Half of the adults with severe hearing loss exhibited a significant (a minimum of p<.05) interaction of bite-block and masking effects, collapsed across vowels. No other group of individual subjects exhibited this trend. Subsequent Post Hoc Tukey HSD tests for unequal sample sizes (See Table 10.18.) revealed that significant differences between conditions resulted for S3F and S5F because conditions moved F2 in different directions. For S3F (See Figure 10.5.) the bite-block condition significantly raised F2, while masking significantly lowered F2, making them significantly different from each other, and each significantly different from the bite-block-plus-masking condition, which caused little change, collapsed across vowels. For S5F (See Figure 10.8.) the masking condition raised F2 while the bite-block-plus-masking condition lowered F2, resulting in a significant difference between them. For subject S6F (see Figure 10.9), F2 was lowered significantly in the bite-block condition and most significantly in the bite-block-plus-masking condition. Clearly, the bite-block-plus-masking condition was most detrimental in that it was shown to be significantly different from both the masking and the bite-block conditions. Further evidence was provided from the individual analysis of the vowel /i/ for S4M. (See Appendix F4e.) A significant (p=.00000) effect of Condition on F2 was found. Subsequent Post Hoc HSD tests for unequal sample sizes revealed that the bite-block-plus-masking condition was significantly (p=.00012) lowered from the normal condition. The bite-block-plus-masking condition was also significantly (p=.00012) lower than the bite-block condition.

Only one of the adults with severe hearing loss, S5F, showed a significant (p<.05) increase in variability of F2 as a result of bite-block conditions, collapsed across /I/ and /ae/. (This subject had no data for /i/. See Table 10.14 for data values.) No significant

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effect of masking or significant interaction of bite-block and masking effects on F2 standard deviation were found for any of the individual adults with severe hearing loss. S2M showed a main effect of vowel on F2 variability, significant at the $p<.05$ level in the bite-block-by-vowel two-way analysis of variance. (See Appendix F2c.) Post Hoc Tukey HSD tests of differences between the standard deviations of F2 of each vowel, collapsed across all conditions, revealed that hit F2SD (100.01) was significantly greater than hat F2SD (51.66), $p=.0257$.

Table 10.16.--Summary of Significant Changes in F2 for Individual Adults with Severe Hearing Loss

Significant Changes in F2						
	S1M	S2M	S3F	S4M	S5F	S6F
Main Effect of Bite Block	↓ ★★	↓ ★★	↑ ★★		↓ ★★	↓ ★★
Main Effect of Masking	↓ ★★	↓ ★★	↓ ★★	↓ ★★		↓ ★★
Main Effect of Vowel	★★	★★	★★	★★	★★	★★
Interaction of Bite Block and Masking			★		★★	★
Significant Changes in F2 Standard Deviation						
	S1M	S2M	S3F	S4M	S5F	S6F
Main Effect of Bite Block					★	
Main Effect of Masking						
Main Effect of Vowel		★				
Interaction of Bite Block and Masking						

★★=$p<.01$, ★=$p<.05$; ↑ = raised formant, ↓ = lowered formant

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F1

Table 10.17 displays, in summary, the statistically significant changes in F1 frequency and F1 variability found for each individual adult with severe hearing loss. A significant (a minimum of $p<.05$) main effect of bite block on F1 was exhibited by five of the six subjects. In all cases, F1 was raised.

Five of six of the adults with severe hearing loss showed a significant (a minimum of $p<.05$) main effect of masking on F1. In three of the five cases, F1 was lowered.

Half of the adults with severe hearing loss showed a significant interaction of bite-block and masking effects on F1. Table 10.18 displays a summary of Post Hoc Tukey HSD tests for unequal sample sizes. The three subjects who exhibited a bite-block-and-masking interaction displayed individual patterns of change. For S1M, F1 was raised from the normal condition a relatively consistent amount in each test condition, collapsed across vowels. (See Figure 10.3.) F1 was also raised for S5F, collapsed over /I/ and /ae/, but only in the bite-block condition and no other test conditions, so the bite-block condition was found to be significantly different from them. (See Figure 10.8.) Conversely, for S3F, collapsed across /i/ and /ae/ only, F1 was lowered significantly in the masking condition, but not in other test conditions, so the masking condition was found to be significantly different from all others. (See Figure 10.5.)

None of the individual adults with severe hearing loss exhibited a significant effect of bite block on F1 standard deviation. No significant effect of masking nor a significant interaction of bite-block and masking effects was seen. A significant (a minimum of $p<.05$) main effect of vowel on the variability of F1 was seen in half of the adults with severe hearing loss. Subsequent Post Hoc Tukey HSD tests revealed, just as they had in all the other groups of individual subjects, the following trend: F1 was most variable in hat, less so in hit, and least in heat, despite condition. (See Table 10.19.)

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Table 10.17.--Summary of Significant Changes in F1 for Individual Adults with Severe Hearing Loss

Significant Changes in F1						
	S1M	S2M	S3F	S4M	S5F	S6F
Main Effect of Bite Block	↑ ★★	↑ ★★	↑ ★★		↑ ★★	↑ ★
Main Effect of Masking	↑ ★★	↑ ★	↓ ★★	↓ ★	↓ ★★	
Main Effect of Vowel	★★	★★	★★	★★	★★	★★
Interaction of Bite Block and Masking	★★		★★		★★	
Significant Changes in F1 Standard Deviation						
	S1M	S2M	S3F	S4M	S5F	S6F
Main Effect of Bite Block						
Main Effect of Masking						
Main Effect of Vowel	★			★	★★	
Interaction of Bite Block and Masking						

★★=p<.01, ★=p<.05; ↑ = raised formant, ↓ = lowered formant

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Table 10.18.--Summary of Post Hoc Tests of Significant Interactions of Bite-Block and Masking Effects (Collapsed Across Vowel) for Individual Adults with Severe Hearing Loss

Significant Differences in F2						
Condition	S1M	S2M	S3F	S4M	S5F	S6F
Normal vs. Bite Block			↑ ★★			↓ ★
Normal vs. Bite Block and Masking						↓ ★★
Normal vs. Masking			↓ ★★			
Masking vs. Bite Block			★★			
Masking vs. Bite Block and Masking			★★		★★	★★
Bite Block vs. Bite Block and Masking			★★			★★
Significant Differences in F1						
Condition	S1M	S2M	S3F	S4M	S5F	S6F
Normal vs. Bite Block	↑ ★★				↑ ★★	
Normal vs. Bite Block and Masking	↑ ★★					
Normal vs. Masking	↑ ★★		↓ ★★			
Masking vs. Bite Block			★★		★★	
Masking vs. Bite Block and Masking			★★			
Bite Block vs. Bite Block and Masking					★★	

★★=p<.01, ★=p<.05; ↑ = raised formant, ↓ = lowered formant

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Table 10.19.--Summary of Results of Post Hoc Tests of the Main Effect of Vowel for F1 Standard Deviation for Adults with Severe Hearing Loss

S1M	Standard Deviation of F1		
	Heat 22.70	Hit 41.65	Hat 54.16
Heat v. Hat	p = .0269★	Bite Block x Vowel Two-Way ANOVA	
Heat v. Hat	p = .0256★	Masking x Vowel Two-Way ANOVA	
S4M	**Standard Deviation of F1**		
	Heat N/A	Hit 33.62	Hat 44.35
Hit v. Hat	p = .0231★	Masking x Vowel Two-Way ANOVA	
S5F	**Standard Deviation of F1**		
	Heat N/A	Hit 26.10	Hat 79.24
Hit v. Hat	p = .0047★★	Bite Block x Vowel Two-Way ANOVA	
Hit v. Hat	p = .0004★★	Masking x Vowel Two-Way ANOVA	

★★ = p<.01, ★ = p<.05

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Change Relative to Vowel Target

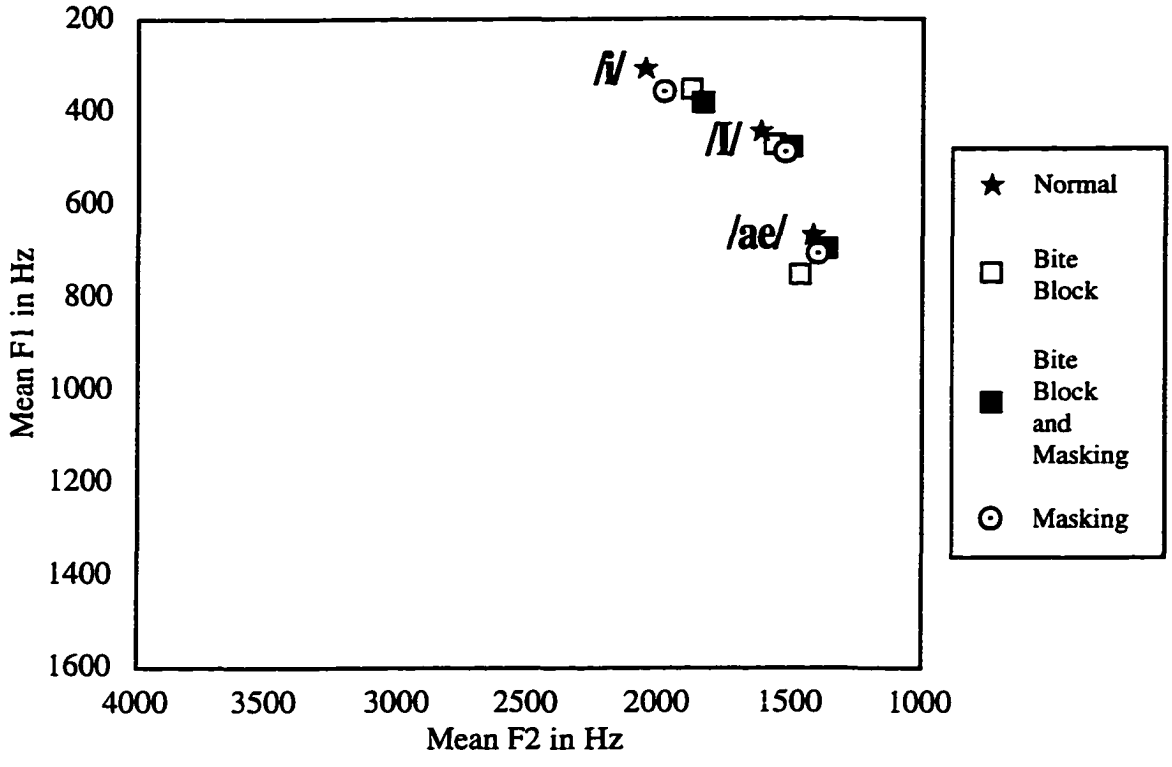
In the previous section, "Magnitude of Change," discussion was given to the results of ANOVAs that examined the effect of test conditions collapsed across vowels. Those same ANOVAs also revealed condition-by-vowel interactions that will be taken up here. It will be seen, both in figures and tests of significance, that some conditions affected some vowels more than others.

First, these effects have been presented graphically for each subject. Figures 10.10 - 10.21 follow. Two figures, identical to those that were displayed for every other individual subject, are presented per page for each of the six adults with severe hearing loss. The figure at the top of the page displays mean F2 and F1 values from each condition in a traditional F1-by-F2 plot of "vowel space." The figures at the bottom of each page present two panels, left and right, of plots of the standard deviation of F2 and F1, respectively. The figures display the varying effects of test condition, depending on vowel target, on both mean formant measures and the variability of production. They also reveal the profiles of articulatory adjustments by each individual.

While the figures illustrate individual differences in the effect of test conditions and articulatory adjustments, one must return to the statistical tests of significance in order to make useful generalizations about conditions that changed the production of some vowels more than others. Summary tables are presented below to consolidate the detailed results. The reader will remember from earlier tables that no bite-block data for hit for subject S3F, no masking data for heat for S4M, and no data for heat for S5F were available, so "N/A" will appear in parts of the tables where those data are missing. All F tables for all of the following reported results may be found for each adult with severe hearing loss (S1-S6) as Appendices F1 - F6, respectively.

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Fig. 10.10. Subject S1M: Mean F1 x F2 Plot of Vowels in Each Condition



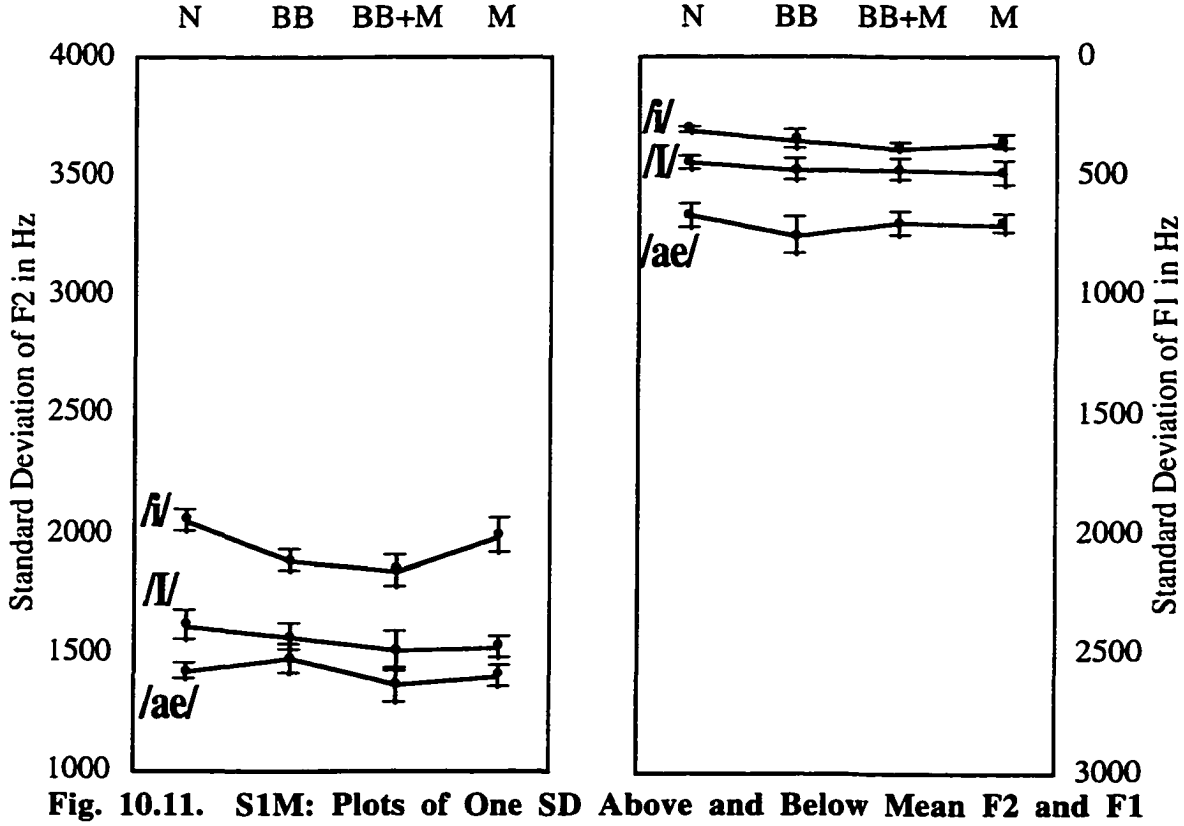
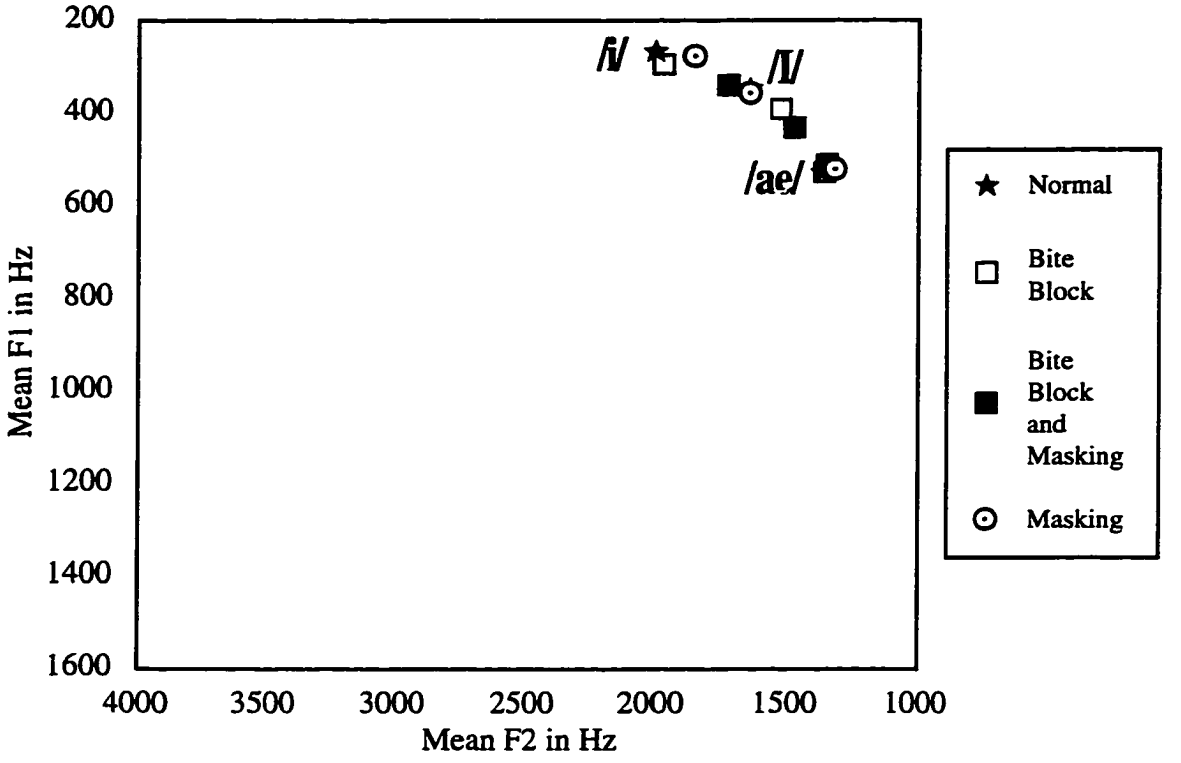


Fig. 10.11. S1M: Plots of One SD Above and Below Mean F2 and F1

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Fig. 10.12. Subject S2M: Mean F1 x F2 Plot of Vowels in Each Condition



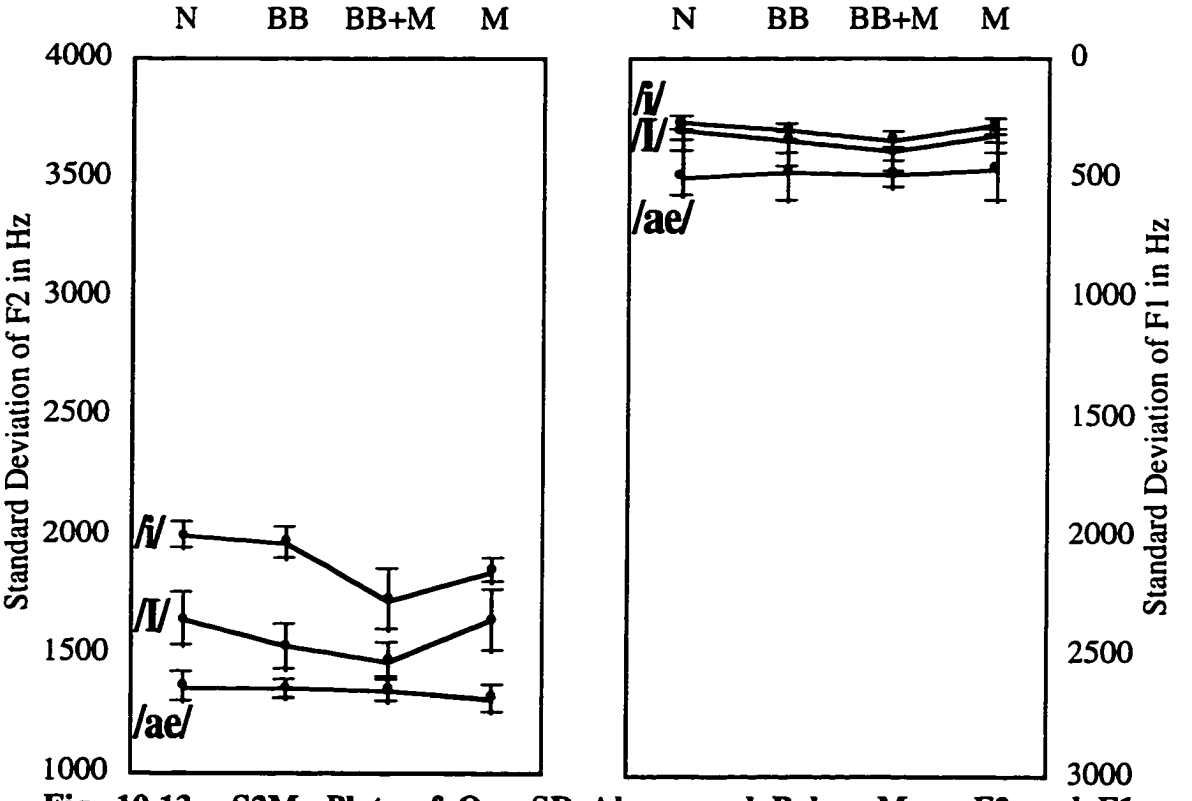
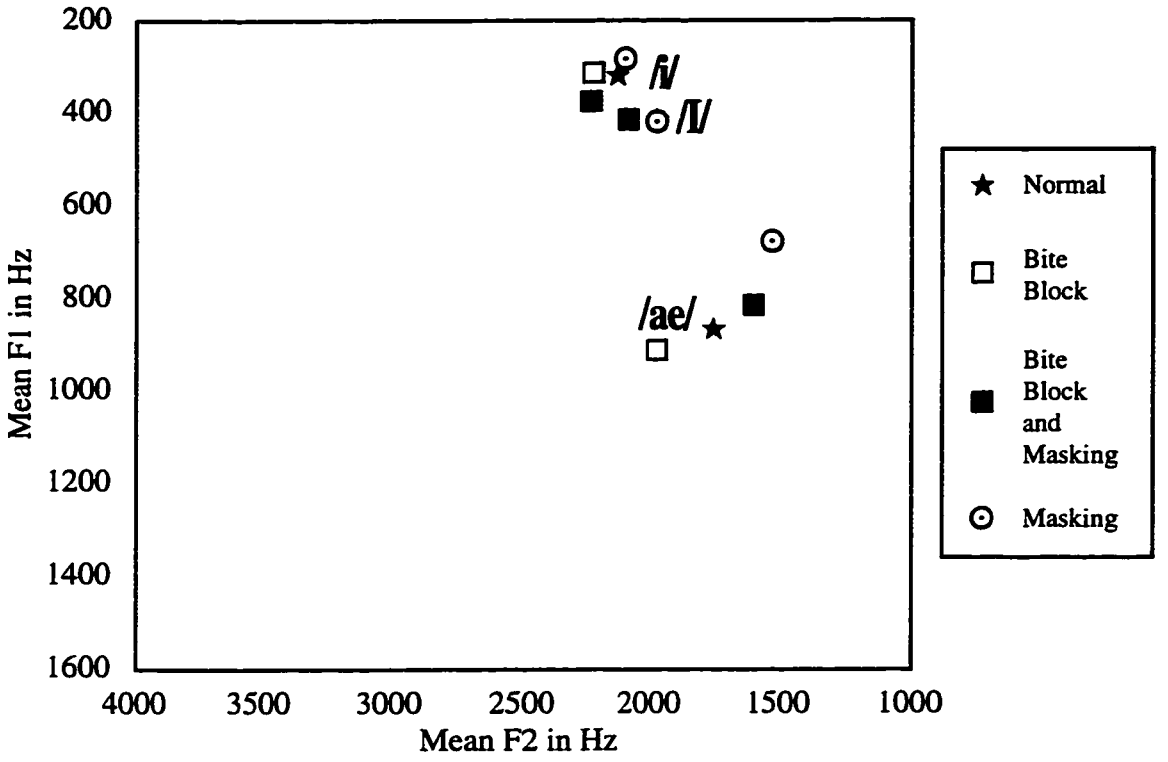


Fig. 10.13. S2M: Plots of One SD Above and Below Mean F2 and F1

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Fig. 10.14. Subject S3F: Mean F1 x F2 Plot of Vowels in Each Condition



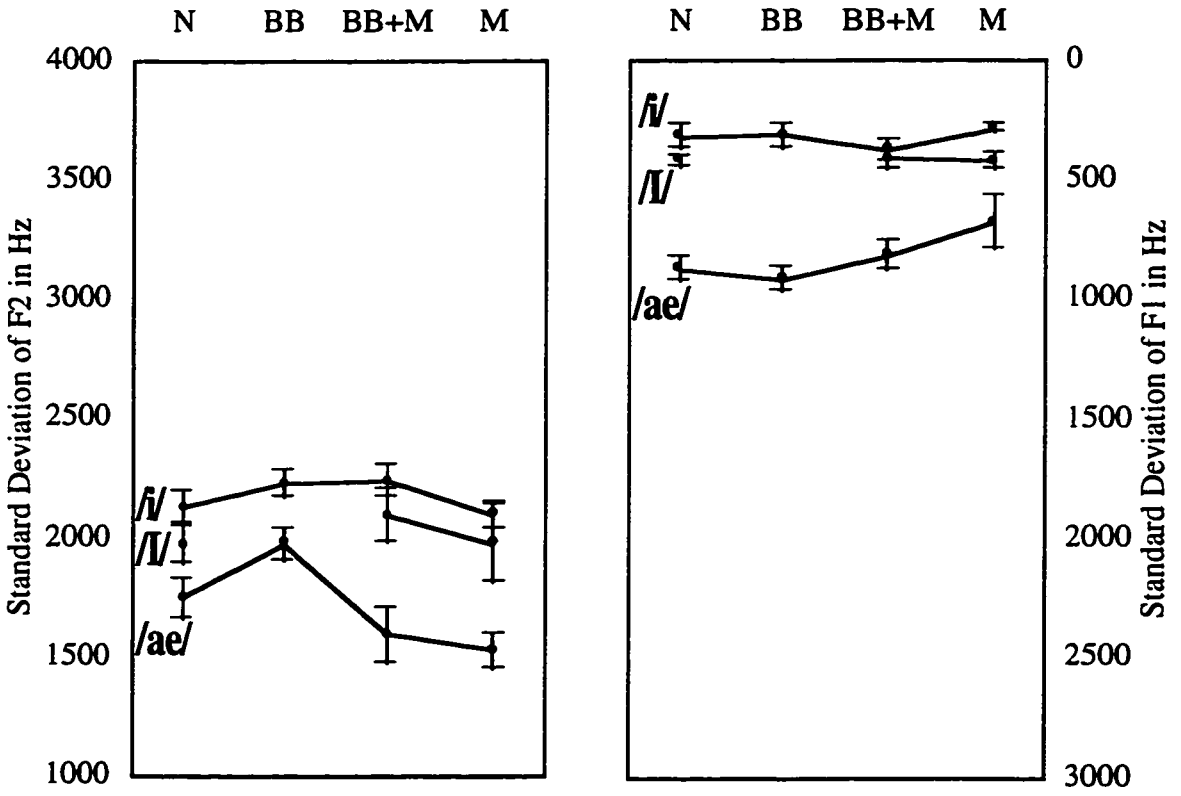
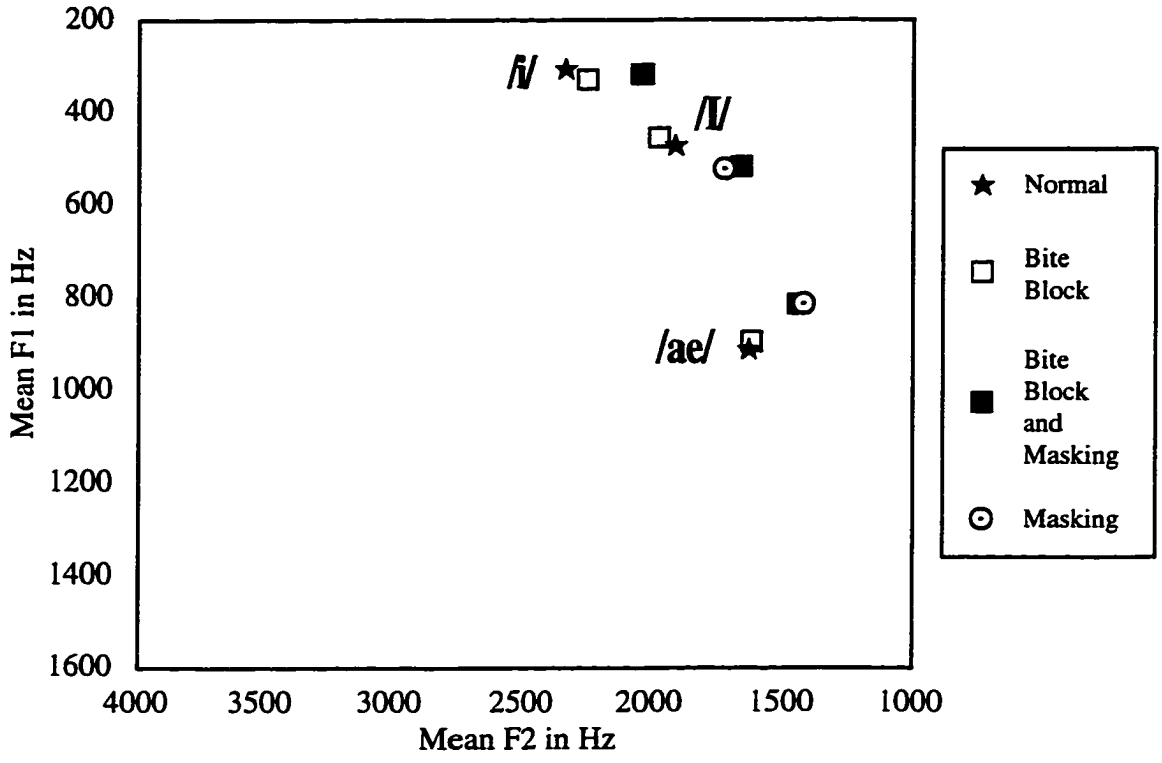


Fig. 10.15. S3F: Plots of One SD Above and Below Mean F2 and F1

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Fig. 10.16. Subject S4M: Mean F1 x F2 Plot of Vowels in Each Condition



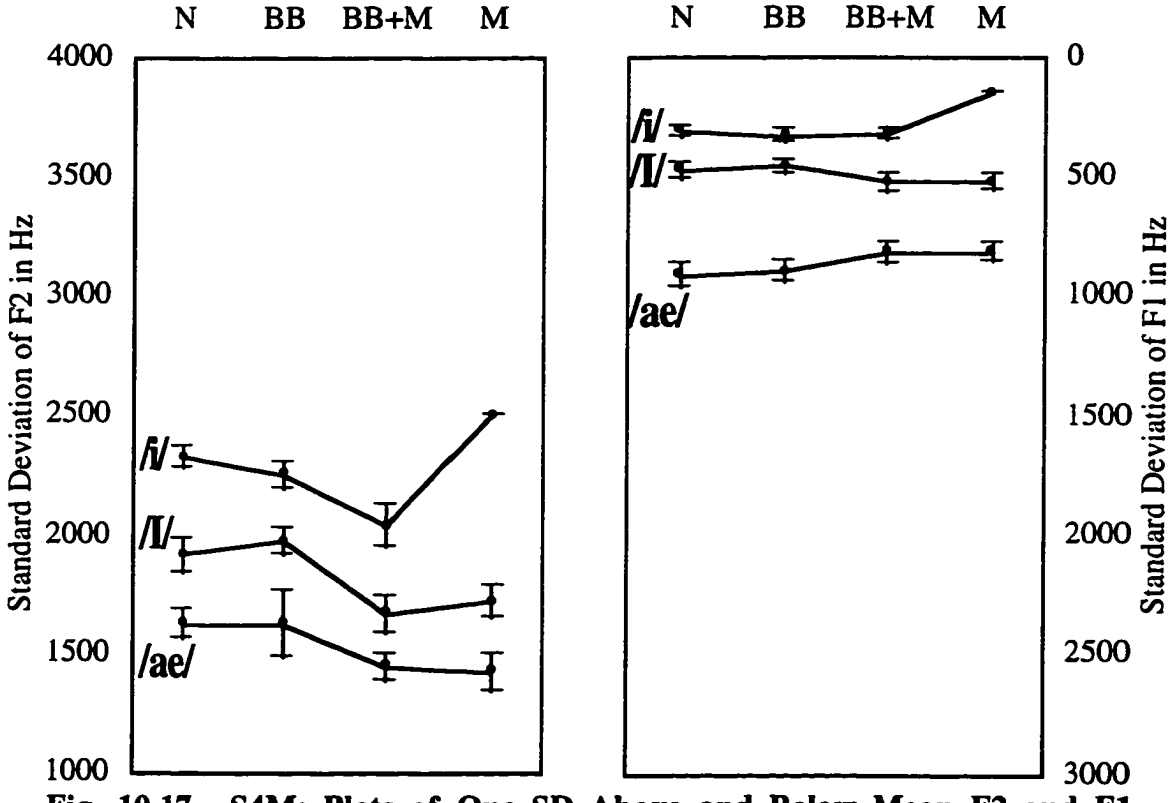
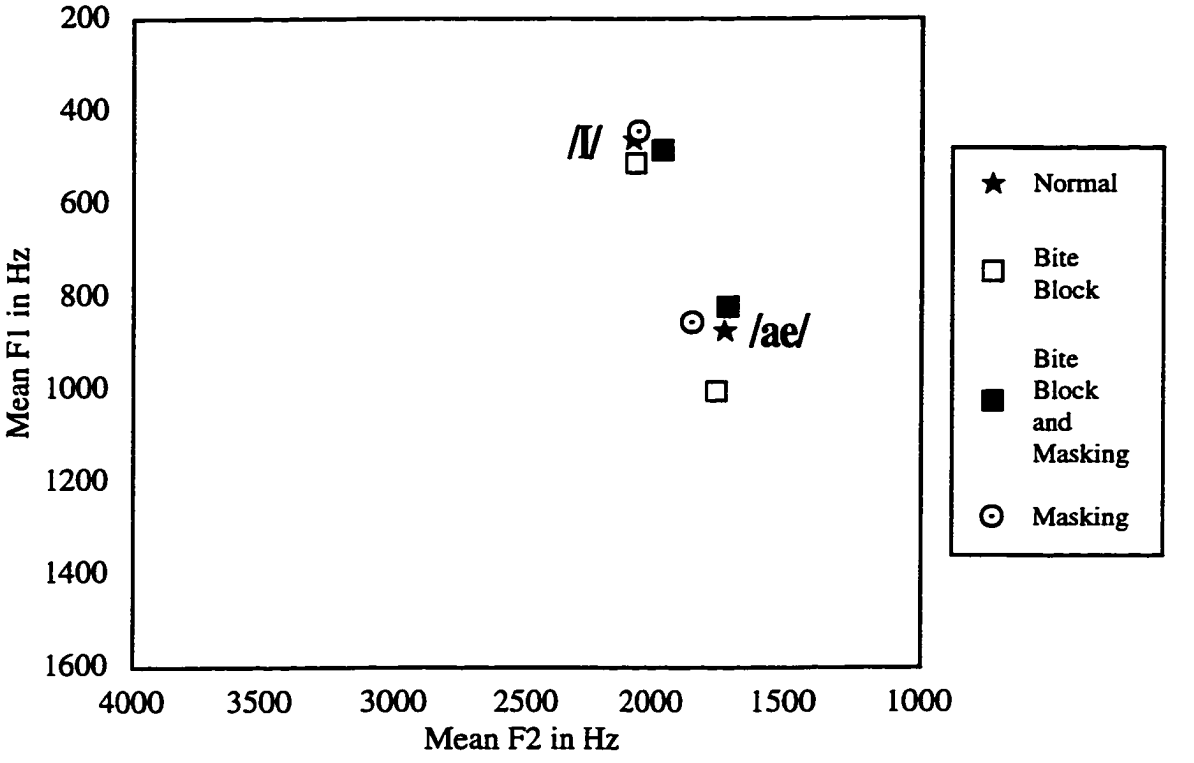


Fig. 10.17. S4M: Plots of One SD Above and Below Mean F2 and F1

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Fig. 10.18. Subject S5F: Mean F1 x F2 Plot of Vowels in Each Condition



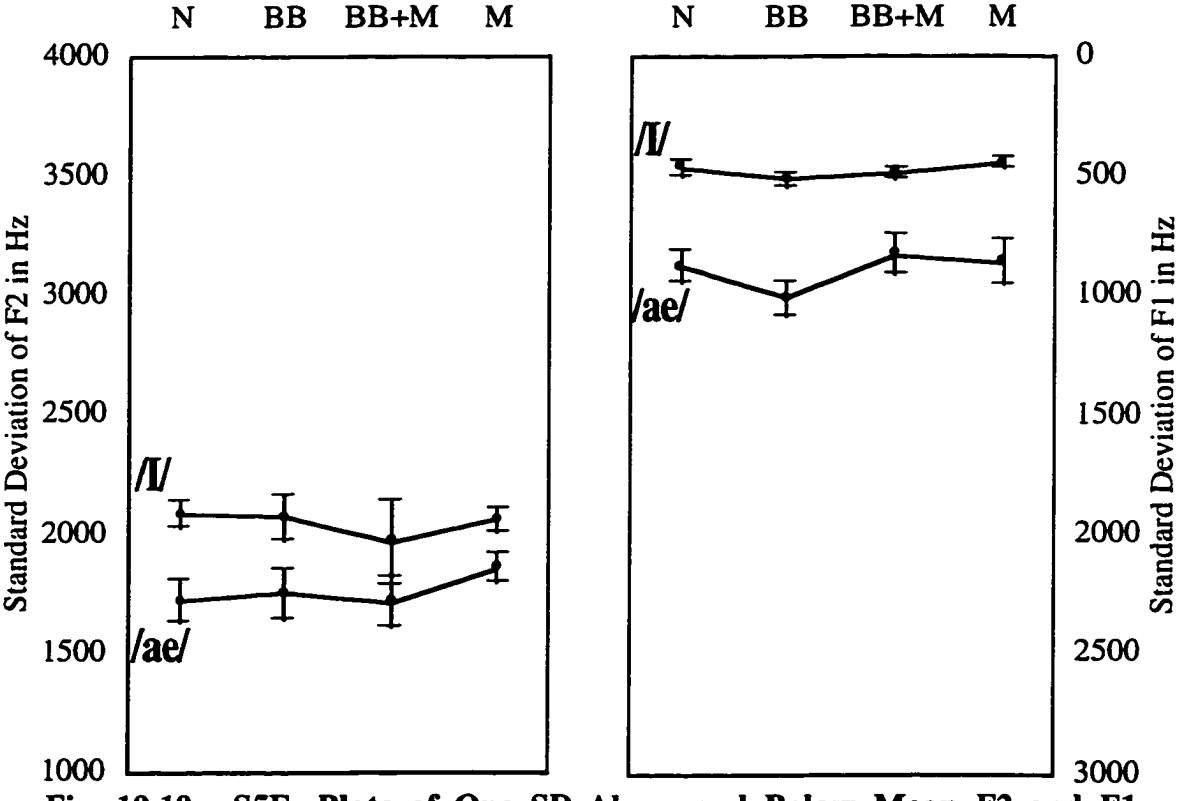
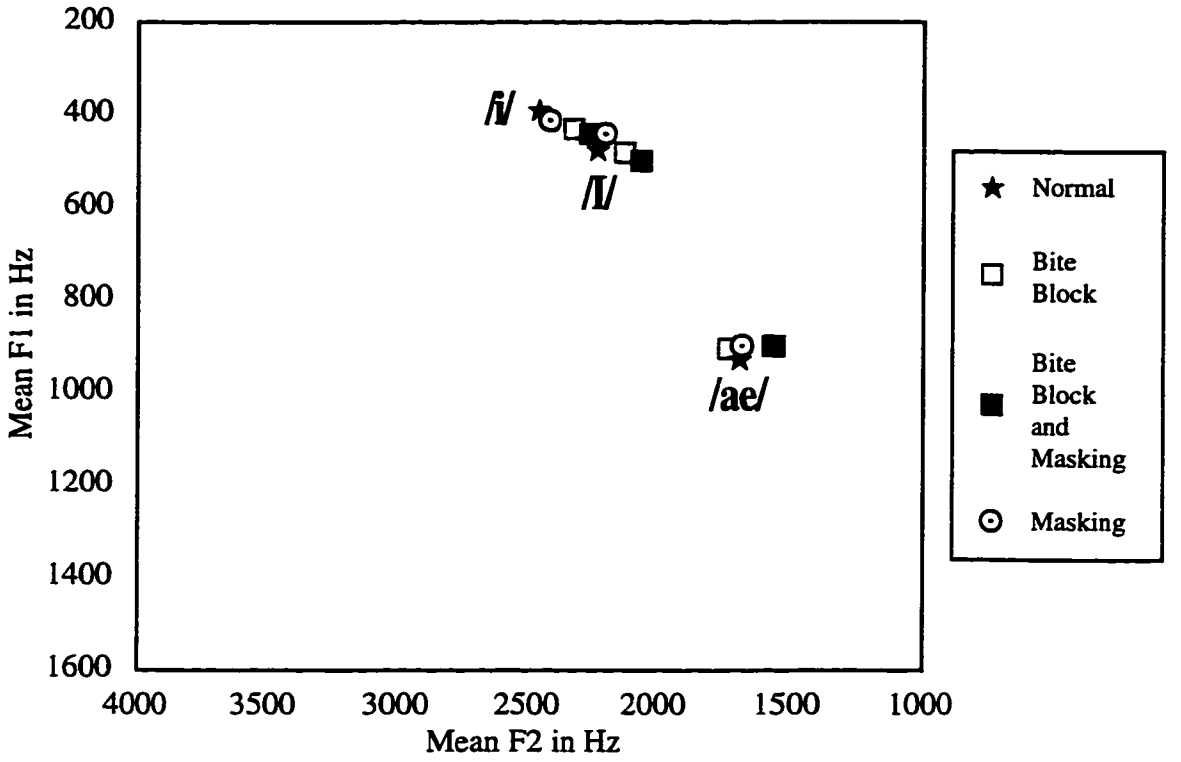


Fig. 10.19. S5F: Plots of One SD Above and Below Mean F2 and F1

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Fig. 10.20. Subject S6F: Mean F1 x F2 Plot of Vowels in Each Condition



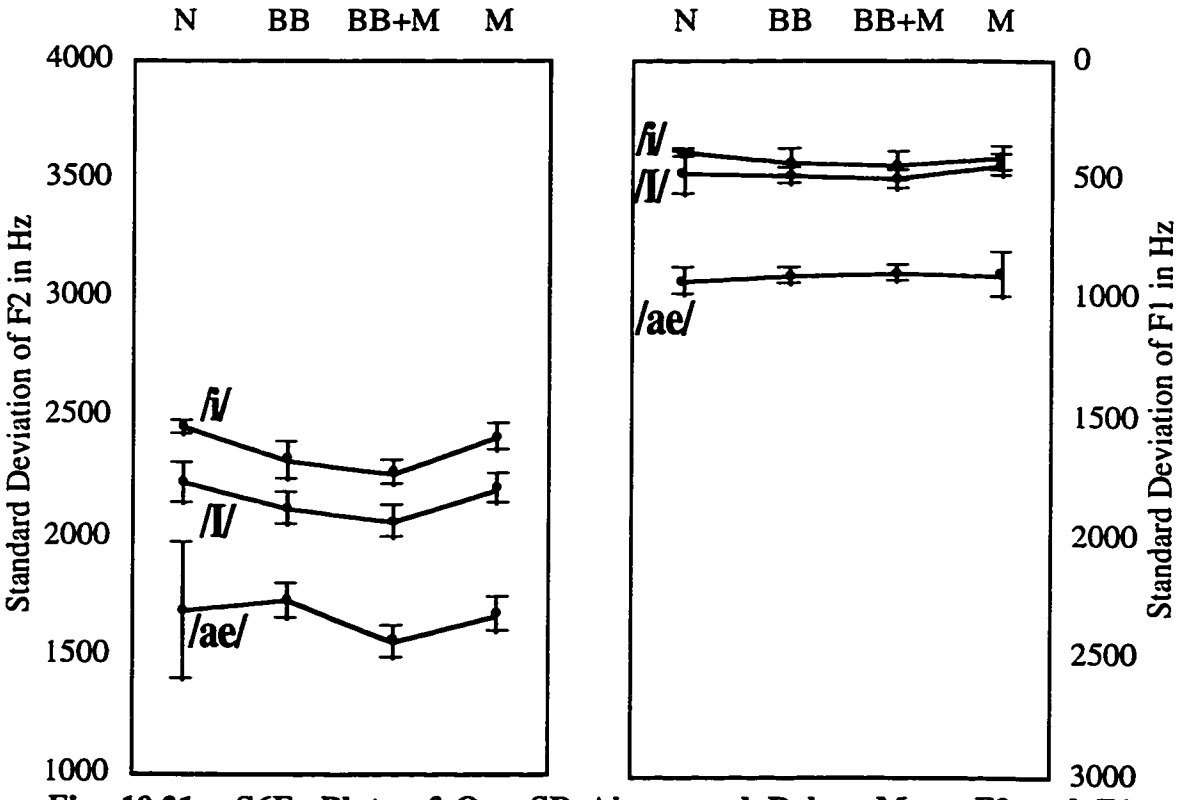


Fig. 10.21. S6F: Plots of One SD Above and Below Mean F2 and F1

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F2

Significant interactions of test and vowel effects on F2 and F2 standard deviation and subsequent Post Hoc tests are summarized in Tables 10.20, 10.22, 10.23, and 10.24.

Table 10.20 shows that a significant interaction ($p<.01$) of bite-block and vowel effects was found for half of the adults with severe hearing loss. The details of this interaction may be examined in a summary of Post Hoc Tukey HSD tests for unequal sample sizes in Table 10.22. For those three adults, F2 in the high vowels /i/ and /I/ was significantly lowered in conditions employing a bite block.

Table 10.20 displays a significant (a minimum of $p<.05$) interaction of masking and vowel effects in four of the six adults with severe hearing loss. Because of missing data, no clear pattern of interaction was revealed in post hoc testing. (See Table 10.23.)

Table 10.20 shows a significant (a minimum of $p<.05$) interaction of bite-block, masking and vowel effects for half of the adults with severe hearing loss. The details of this interaction may be examined in a summary of Post Hoc Tukey HSD tests for unequal sample sizes in Table 10.24. It should be noted that where significant, the results from one-way ANOVAs for Condition on F2 for /I/ for S3F and for /i/ for S4M were included in this table. If one compares Figures 10.10, 10.14 and 10.16 (for S1M, S3F, and S4M, respectively) with Table 10.24, a pattern is revealed that suggests that bite-block conditions affected /i/ F2 more than did masking. For /I/, however, masking conditions appeared to affect F2 more than did the bite-block condition. For /ae/ F2, masking conditions had a lowering effect, while the bite-block condition raised F2.

Only one adult with severe hearing loss showed a significant interaction of bite-block and vowel effects on F2 variability (See Table 10.20.), however, Post Hoc Tukey HSD testing failed to reveal any meaningful significant differences. No interaction of masking and vowel effects was seen on F2 standard deviation.

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Table 10.20.--Summary of Significant Interactions of Test and Vowel Effects on F2 in Individual Adults with Severe Hearing Loss

Significant Interactions of Effects on F2						
	S1M	S2M	S3F	S4M	S5F	S6F
Interaction of Bite Block and Vowel	★★	★★				★★
Interaction of Masking and Vowel		★★	★★	★	★★	
Interaction of Bite Block, Masking, and Vowel	★★		★★	★		
Significant Interactions of Effects on F2 Standard Deviation						
	S1M	S2M	S3F	S4M	S5F	S6F
Interaction of Bite Block and Vowel		★				
Interaction of Masking and Vowel						

★★=p<.01, ★=p<.05

F1

Significant interactions of test conditions and vowel targets on F1 and F1 standard deviation and subsequent Post Hoc Tukey HSD tests are summarized in Tables 10.21, 10.22, 10.23, and 10.25.

Table 10.21 shows that a significant (a minimum of p<.05) interaction of bite-block and vowel effects on F1 was found for half of the adults with severe hearing loss. The details of these interactions may be examined in a summary of Post Hoc Tukey HSD tests for unequal sample sizes in Table 10.22. A consistent pattern of interaction was not revealed, in part because /I/ data were missing for S3F.

Table 10.21 displays a significant interaction (a minimum of p<.05) of masking and vowel effects in five of six of the adults with severe hearing loss. The details of these interactions may be seen in a summary of Post Hoc Tukey HSD tests for unequal sample sizes in Table 10.23. A clear pattern of interaction was not revealed, in part because of

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missing data for subjects S3F, S4M and S5F. However, there was some suggestion that masking was particularly detrimental to F1 in /ae/.

Table 10.21.--Summary of Significant Interactions of Test and Vowel Effects on F1 in Individual Adults with Severe Hearing Loss

Significant Interactions of Effects on F1						
	S1M	S2M	S3F	S4M	S5F	S6F
Interaction of Bite Block and Vowel		★★	★			★
Interaction of Masking and Vowel	★★	★	★★	★★	★★	
Interaction of Bite Block, Masking, and Vowel					★★	
Significant Interactions of Effects on F1 Standard Deviation						
	S1M	S2M	S3F	S4M	S5F	S6F
Interaction of Bite Block and Vowel						
Interaction of Masking and Vowel					★	

★★=p<.01, ★=p<.05

Table 10.21 shows a significant (p<.01) interaction of bite-block, masking and vowel effects in only one of the adults with severe hearing loss. The details of this interaction may be examined in a summary of Post Hoc Tukey HSD tests for unequal sample sizes in Table 10.25. Again, there were no data for /i/ for S5F, but if one compares the details of Table 10.25 with Figure 10.18, it is apparent that the bite-block condition raised /ae/ F1, while the other test conditions did not.

None of the adults with severe hearing loss showed a significant interaction of bite block and vowel on F1 variability. (See Table 10.21.) Only S5F exhibited a significant interaction of masking and vowel, but Post Hoc Tukey HSD tests revealed no meaningful significant differences.

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Table 10.22.--Summary of Post Hoc Tests of Significant Interactions of Bite-Block and Vowel Effects (Collapsed Across Masking) for Individual Adults with Severe Hearing Loss

Significant Differences in F2						
Condition and Vowel	S1M	S2M	S3F	S4M	S5F	S6F
No Bite-Block "heat" vs. Bite-Block "heat"	↓ ★★	↓ ★★				↓ ★★
No Bite-Block "hit" vs. Bite-Block "hit"		↓ ★★				↓ ★★
No Bite-Block "hat" vs. Bite-Block "hat"						
Significant Differences in F1						
Condition and Vowel	S1M	S2M	S3F	S4M	S5F	S6F
No Bite-Block "heat" vs. Bite-Block "heat"		↑ ★★				
No Bite-Block "hit" vs. Bite-Block "hit"		↑ ★★	Did Not Test			
No Bite-Block "hat" vs. Bite-Block "hat"			↑ ★★			

Table 10.23.--Summary of Post Hoc Tests of Significant Interactions of Masking and Vowel Effects (Collapsed Across Bite Block) for Individual Adults with Severe Hearing Loss

Significant Differences in F2						
Condition and Vowel	S1M	S2M	S3F	S4M	S5F	S6F
No Masking "heat" vs. Masking "heat"		↓ ★★		Did Not Test	N/A	
No Masking "hit" vs. Masking "hit"			Did Not Test	↓ ★★		
No Masking "hat" vs. Masking "hat"			↓ ★★	↓ ★★		
Significant Differences in F1						
Condition and Vowel	S1M	S2M	S3F	S4M	S5F	S6F
No Masking "heat" vs. Masking "heat"	↑ ★★			Did Not Test	N/A	
No Masking "hit" vs. Masking "hit"			Did Not Test	↑ ★★		
No Masking "hat" vs. Masking "hat"			↓ ★★	↓ ★★	↓ ★★	

★★=p<.01, ★=p<.05; ↑ = raised formant, ↓ = lowered formant

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Table 10.24.--Summary of Post Hoc Tests of Significant Interactions of Bite-Block, Masking, and Vowel Effects on F2 for Individual Adults with Severe Hearing Loss

Significant Differences in F2						
Condition and Vowel	S1M	S2M	S3F	S4M	S5F	S6F
Normal "heat" vs. Bite-Block "heat"	★★			★		
Normal "heat" vs. Bite-Block-plus-Masking "heat"	★★		★	★★		
Normal "heat" vs. Masking "heat"				N/A		
Masking "heat" vs. Bite-Block "heat"	★★		★★	N/A		
Masking "heat" vs. Bite-Block-plus-Masking "heat"	★★		★★	N/A		
Bite Block "heat" vs. Bite-Block-plus-Masking "heat"				★★		
Normal "hit" vs. Bite-Block "hit"						
Normal "hit" vs. Bite-Block-plus-Masking "hit"	★★			★★		
Normal "hit" vs. Masking "hit"	★★			★★		
Masking "hit" vs. Bite-Block "hit"				★★		
Masking "hit" vs. Bite-Block-plus-Masking "hit"						
Bite Block "hit" vs. Bite-Block-plus-Masking "hit"				★★		
Normal "hat" vs. Bite-Block "hat"			★★			
Normal "hat" vs. Bite-Block-plus-Masking "hat"			★★	★★		
Normal "hat" vs. Masking "hat"			★★	★★		
Masking "hat" vs. Bite-Block "hat"	★		★★	★★		
Masking "hat" vs. Bite-Block-plus-Masking "hat"						
Bite Block "hat" vs. Bite-Block-plus-Masking "hat"	★★		★★	★★		

★★=p<.01, ★=p<.05; direction of change illustrated in Figures 10.21 - 10.23

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Table 10.25.--Summary of Post Hoc Tests of Significant Interactions of Bite-Block, Masking, and Vowel Effects on F1 for Individual Adults with Severe Hearing Loss

Significant Differences in F1						
Condition and Vowel	S1M	S2M	S3F	S4M	S5F	S6F
Normal "heat" vs. Bite-Block "heat"					N/A	
Normal "heat" vs. Bite-Block-plus-Masking "heat"					N/A	
Normal "heat" vs. Masking "heat"					N/A	
Masking "heat" vs. Bite-Block "heat"					N/A	
Masking "heat" vs. Bite-Block-plus-Masking "heat"					N/A	
Bite Block "heat" vs. Bite-Block-plus-Masking "heat"					N/A	
Normal "hit" vs. Bite-Block "hit"						
Normal "hit" vs. Bite-Block-plus-Masking "hit"						
Normal "hit" vs. Masking "hit"						
Masking "hit" vs. Bite-Block "hit"						
Masking "hit" vs. Bite-Block-plus-Masking "hit"						
Bite Block "hit" vs. Bite-Block-plus-Masking "hit"						
Normal "hat" vs. Bite-Block "hat"					★★	
Normal "hat" vs. Bite-Block-plus-Masking "hat"						
Normal "hat" vs. Masking "hat"						
Masking "hat" vs. Bite-Block "hat"					★★	
Masking "hat" vs. Bite-Block-plus-Masking "hat"						
Bite Block "hat" vs. Bite-Block-plus-Masking "hat"					★★	

★★=p<.01, ★=p<.05; direction of change illustrated in Figures 10.21 - 10.23

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Summary

Tables 10.28 - 10.31 facilitate the comparison of bite-block, masking, and bite-block-plus-masking effects on all dependent variables, to show patterns revealed by the majority of individual talkers within and across each subject group.

The data from individual adults with severe hearing loss revealed that:

A. There was a significant ($p<.01$) main effect of bite block on F2 for a majority of these subjects. (See Table 10.28.) /i/ and /I/ F2 were lowered and /ae/ F2 was raised. Half of the subjects showed a bite-block-by-vowel interaction wherein the high vowels were most often affected significantly by the bite block. With the exception of the raised F2 in /ae/, the direction of change shown by these subjects was similar to that of the adults and the children with normal hearing, who also exhibited a lowered F2. The adults with profound hearing loss exhibited a raised /I/ F2 and an /i/ F2 that was raised as often as it was lowered, making their direction of change different from the other three groups. It was noted that subject S3F, who had the greatest hearing loss in the group of adults with severe hearing loss, also exhibited patterns of F2 raising in the high vowels in several test conditions. The range of percent change was highly similar in the adults with severe and profound hearing loss, and more restricted than in the adults and the children with normal hearing. A majority of the subjects also exhibited a significant main effect of bite block on F1. F1 was raised in /i/ and /I/, but /ae/ was lowered as often as it was raised. In terms of direction, these subjects looked similar to the adults and the children with normal hearing for /i/ and /I/, but for /ae/, there was a similarity between the adults with severe and profound hearing loss, in that F1 was raised as often as it was lowered. Range of percent change was most restricted in this group.

B. A main effect of masking on F2 was found for a majority of these severely hearing-impaired subjects. (See Table 10.29.) In fact, a main effect of masking was found for a majority within every adult group, but not in the children. The direction of change in

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F2 is identical to that of the adults with normal hearing, and both contrast with the numerous cases of a raised F2 in the children and the adults with profound hearing loss. Range of percent change in F2 in the masking condition was greater in the adults with profound and severe hearing loss than in the adults and the children with normal hearing! A main effect of masking was also shown for F1 in a majority of these subjects. The adults with profound hearing loss were the only individuals who did not show a main effect of masking on F1. /i/ F1 was raised in every group and /I/ F1 was generally raised, but masking effects on /ae/ were varied across groups and the severely hearing-impaired adults were the only subjects who exhibited a pattern of lowering.

C. A significant interaction of bite block and masking on F2 was found in half of the adults with severe hearing loss. This was the only subject group to exhibit such. (See Table 10.30.) Collapsed across vowels, there was much individual variability with one subject (S3F) affected more by bite block and masking alone than by the combined condition, while another (S6F) showed almost no effect of masking, a significant effect of bite block, and the greatest change in the combined condition. Direction of change was identical to the adults and the children with normal hearing, such that the adults with profound hearing loss were shown to be unique in the pattern of raising F2 in the high vowels. An interaction of bite block, masking and vowel was also shown in half of the subjects. Figures 10.21 - 10.23 provide an overview of direction and magnitude of formant changes in every individual adult with severe hearing loss. Where subjects exhibited a significant interaction of bite block, masking and vowel, post hoc tests were conducted for differences. (See Tables 10.20, 10.21, 10.24, and 10.25.) Those post hoc tests that showed significant differences between normal and test conditions are identified by stars in Figures 10.21 - 10.23. Post hoc tests revealed what Figures 10.21 - 10.23 illustrate, that /i/ F2 was more affected by bite-block and bite-block-plus-masking conditions than by masking and that /I/ F2 was more affected by masking and bite-block-plus-masking conditions than by bite block alone, while /ae/ presented no

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particular trend. An interaction of bite block and masking on F1 was also shown for half of these subjects. Collapsed across vowels, patterns of change varied by individual. For example, test conditions all had about an equal effect for subject S1M, masking had the most affect on S3F, but only the bite block had a significant effect for S5F. F1 in /i/ and /I/ was raised for this and all other groups of individuals, but /ae/ F1 exhibited a pattern of lowering in all but the adults with normal hearing.

D. Test conditions did not result in changes in variability of production for F2 or F1. (See Table 10.31.) Only the children with normal hearing and the adults with profound hearing loss showed an effect of bite block on F2 and F1 variability, respectively. However, just like the individuals in the other subject groups, half of the adults with severe hearing loss showed a significant main effect of vowel for F1. F1 was most variable in hat, less so in hit, and least in heat, collapsed across condition.

E. Individual subjects varied in their ability to compensate in test conditions. One of the more interesting findings in this regard was the direction of F2 change in subject S3F, who exhibited F2 raising in the close vowels /i/ and /I/, while the other individuals in this group, who had more residual hearing, exhibited F2 lowering. (See Figures 10.22 - 10.23.)

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Table 10.26.--Summary of Bite-Block Effects on F2 and F1 for the Majority of Individual Subjects

	Adults with Normal Hearing	Children with Normal Hearing	Adults with Profound Hearing Loss	Adults with Severe Hearing Loss
F2 Direction of Change: heat hit hat	 lowered lowered lowered	 lowered lowered lowered	 unclear raised lowered	 lowered lowered raised
Range of % Change	.23 - 16.58%	.22 - 24.48	.48 - 12.21	.14 - 12.79
Main Effect of Bite Block	★★(all)	★/★★(all)	★★	★★
BB-by-Vowel Interaction	★/★★	★/★★(half)	★★	★★(half)
Details of Interaction:	individual variation in affected vowel targets	/i/ most often affected; /I/ also, but less often	/i/ most often affected	/i/ most often affected; /I/ also, but less often
F1 Direction of Change: heat hit hat	 raised raised lowered	 raised raised lowered	 raised unclear unclear	 raised raised unclear
Range of % Change	.38 - 24.25%	1.85 - 40.43	.05 - 26.28	.19 - 15.31
Main Effect of Bite Block	★/★★	★/★★	★★(half)	★/★★
BB-by-Vowel Interaction	★/★★(all)	★/★★	★★	★/★★(half)
Details of Interaction:	hat most often affected	hat most often affected	hat most often affected	no apparent trend, partly because of missing data

★★=p<.01, ★=p<.05

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Table 10.27.--Summary of Masking Effects on F2 and F1 for the Majority of Individual Subjects

	Adults with Normal Hearing	Children with Normal Hearing	Adults with Profound Hearing Loss	Adults with Severe Hearing Loss
F2 Direction of Change: heat hit hat	 lowered lowered lowered	 lowered raised unclear	 unclear raised raised	 lowered lowered lowered
Range of % Change	.43 - 5.4%	.15 - 6.09	.36 - 13.18	.06 - 12.71
Main Effect of Masking	★/★★		★/★★	★★
M-by-Vowel Interaction	★/★★			★/★★
Details of Interaction:	N1M and N6M particularly affected by masking for all vowels			no apparent trend, partly because of missing data
F1 Direction of Change: heat hit hat	 raised raised raised	 raised raised unclear	 raised unclear unclear	 raised raised lowered
Range of % Change	.22 - 18.8%	.35 - 33.68	.15 - 10.89	1.12 - 21.89
Main Effect of Masking	★/★★(all)	★/★★		★/★★
M-by-Vowel Interaction	★/★★	★/★★(half)	★/★★(half)	★/★★
Details of Interaction:	heat and hit most often affected	hat most often affected	no meaningful patterns shown	trend for hat to be frequently lowered

★★=p<.01, ★=p<.05

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Table 10.28.--Summary of Bite-Block-plus-Masking Effects on F2 and F1 for the Majority of Individual Subjects

	Adults with Normal Hearing	Children with Normal Hearing	Adults with Profound Hearing Loss	Adults with Severe Hearing Loss
F2 Direction of Change: heat hit hat	 lowered lowered lowered	 lowered lowered lowered	 raised unclear lowered	 lowered lowered lowered
Range of % Change	.66 - 16.71%	.52 - 13.88	.51 - 17.36	.35 - 13.00
Interaction of BB and M				★/★★(half)
Interaction of BB and M and Vowel	★/★★			★/★★(half)
Details of Interactions: heat hit hat	 affected more by B+M than by BB or M alone no overall pattern affected more by B+M than by BB or M alone			heat: affected more by BB and B+M than M alone hit: M and B+M affected more than BB alone hat: no overall pattern
F1 Direction of Change: heat hit hat	 raised raised raised	 raised raised lowered	 raised raised lowered	 raised raised lowered
Range of % Change	.44 - 36.67%	1.9 - 45.41	.53 - 27.53	.98 - 27.45
Interaction of BB and M	★/★★		★/★★(half)	★★(half)
Interaction of BB and M and Vowel	★/★★			
Details of Interactions: in general heat hit hat	 M and B+M more detrimental than BB alone little effect B+M detrimental for N4F and N6M BB and B+M more detrimental than masking alone			

★★=p<.01, ★=p<.05

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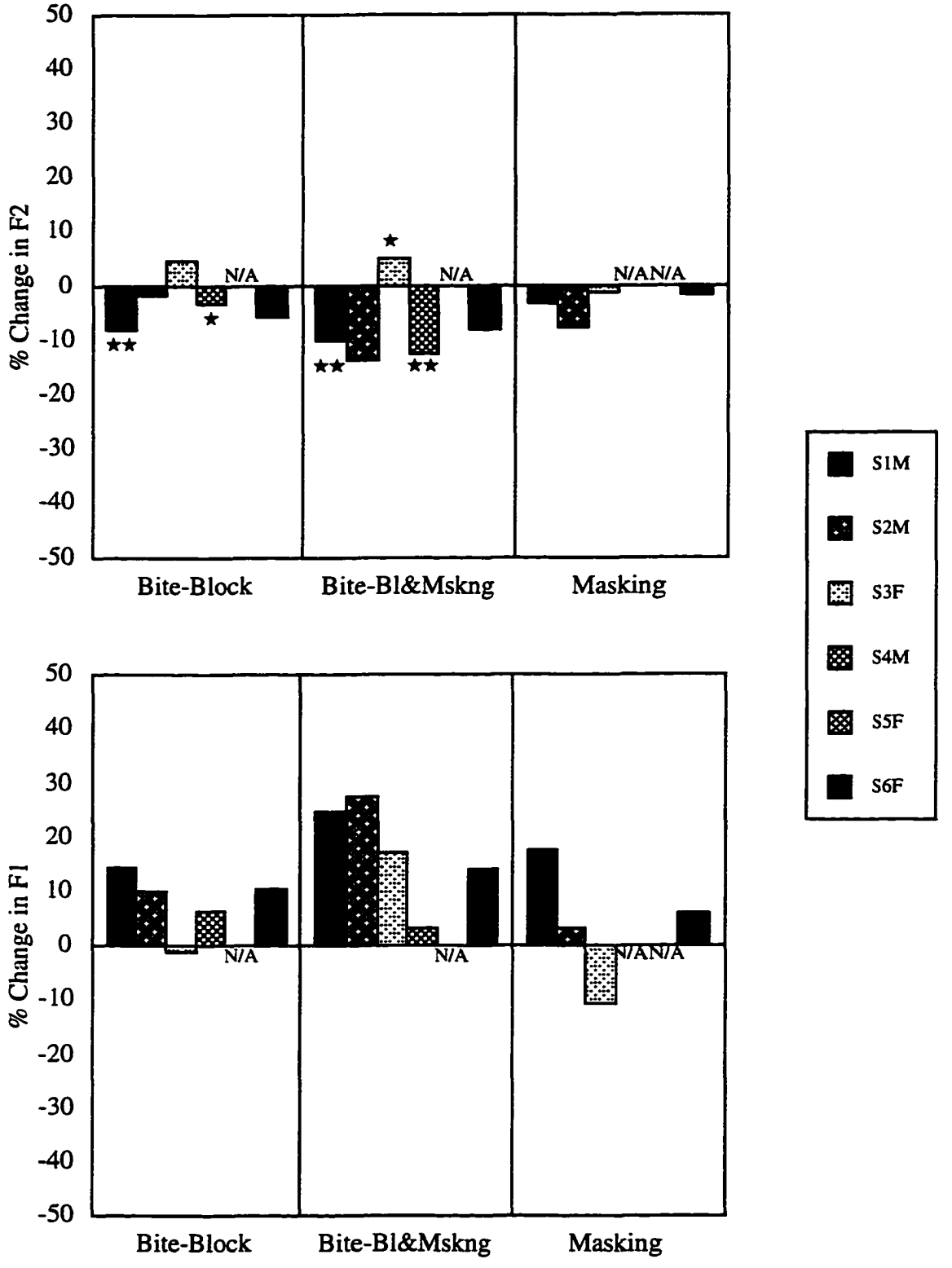
Table 10.29.--Summary of All Test Effects on F2 and F1 Variability for the Majority of Individual Subjects

	Adults with Normal Hearing	Children with Normal Hearing	Adults with Profound Hearing Loss	Adults with Severe Hearing Loss
Main Effect of Bite Block		↑ ★/★★(half)		
Interaction of BB and V				
Main Effect of Masking				
Interaction of M and V				
Interaction of BB and M				
Main Effect of Vowel				
Details of Interactions:				
Main Effect of Bite Block			↑ ★/★★	
Interaction of BB and V				
Main Effect of Masking				
Interaction of M and V				
Interaction of BB and M				
Main Effect of Vowel	★/★★(all)	★/★★(half)	★★(half)	★/★★(half)
Details of Interactions:				
heat	least variability	least variability	least variability	least variability
hit	more variability	more variability	more variability	more variability
hat	greatest variability	greatest variability	greatest variability	greatest variability

★★=p<.01, ★=p<.05; ↑ = increased variability, ↓ = decreased variability

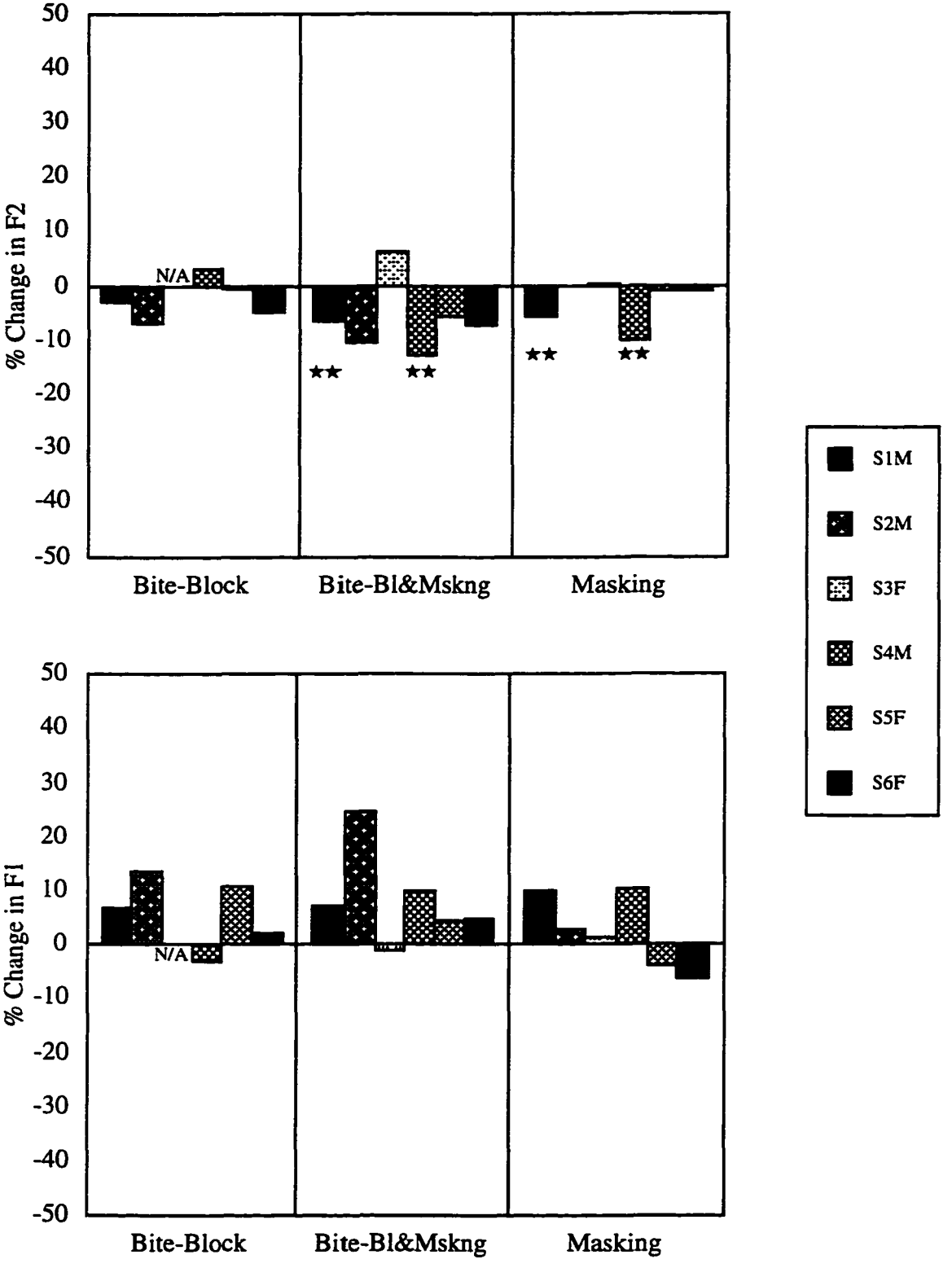
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Fig. 10.22. Overview of Changes in F2 and F1 in /i/ for Each Adult with Severe Hearing Loss



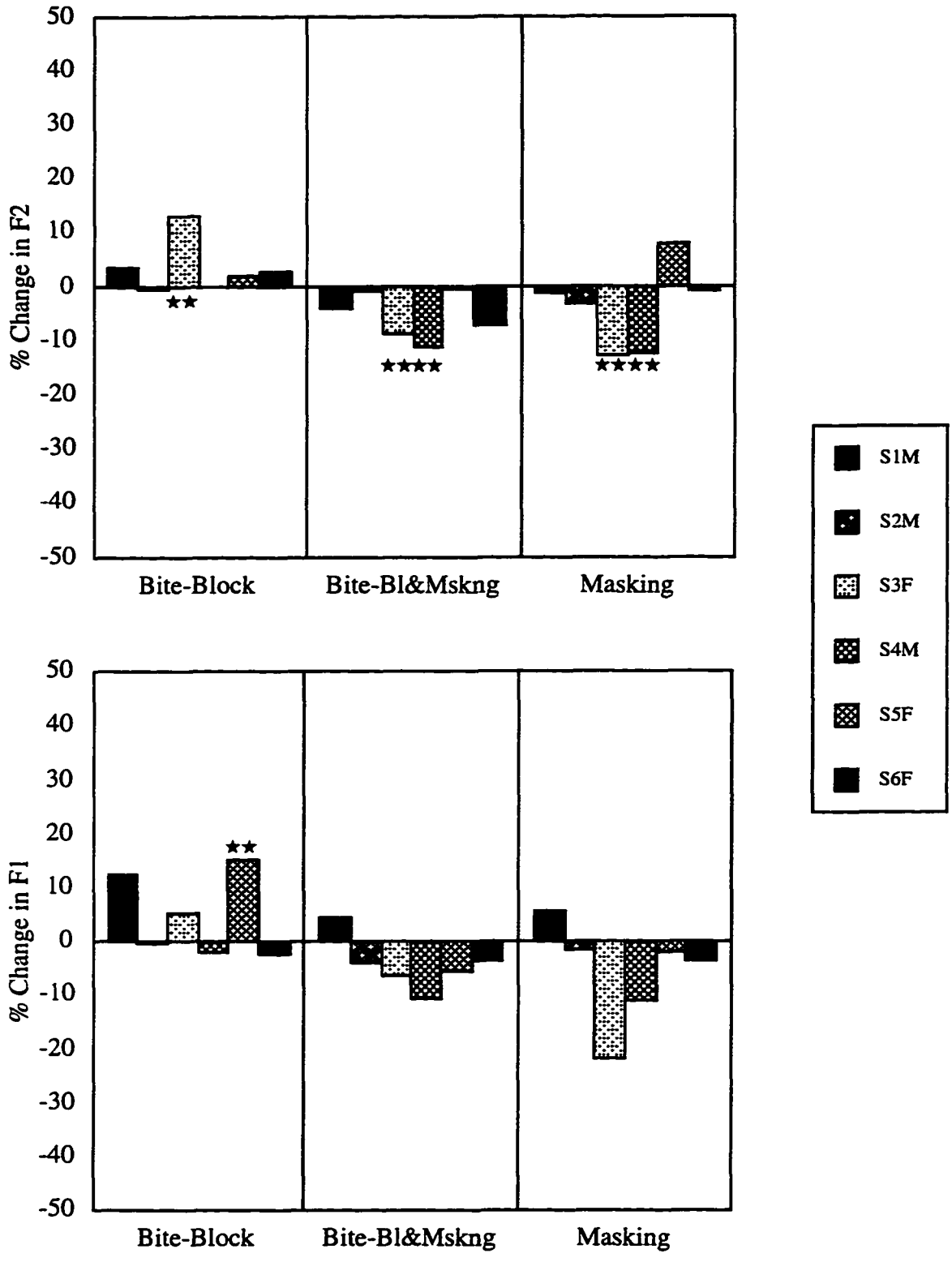
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Fig. 10.23. Overview of Changes in F2 and F1 in /I/ for Each Adult with Severe Hearing Loss



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Fig. 10.24. Overview of Changes in F2 and F1 in /ae/ for Each Adult with Severe Hearing Loss



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Summary of Results from Adults with Severe Hearing Loss

Bite-Block Effects

Observations here are drawn from Tables 10.4 and 10.28.

The bite block lowered F2 in /i/ and /I/, across the group and in a majority of individuals. F2 lowering was predicted by computer simulation. However, /ae/ F2 was raised. While a main effect of condition was shown for F2 in every vowel for the group, post hoc tests revealed no significant effect of bite block. A majority of individuals, on the other hand, exhibited a main effect of bite block on F2. Half showed a bite-block-by-vowel interaction that revealed that the high vowels, /i/ and /I/ were most affected by the bite block.

The group showed a pattern of a raised F1 for every vowel, but when analyzed by individual, it was seen that /ae/ F1 was lowered as often as it was raised. Computer simulation predicted that F1 would be raised in /i/ and /I/, but might be raised or lowered in /ae/, if the bite block created a greater-than-normal or less-than-normal interincisal distance. While a significant main effect of condition was shown for /i/ and /ae/ F1, post hoc tests revealed no significant effects of bite block for the group. However, a majority of individuals showed a main effect of bite block, but no particular pattern of bite block and vowel interaction.

Comparing across all groups and individuals, the direction of change in F2 in the adults with severe hearing loss is more like that in the adults and the children with normal hearing, in that the high vowels are lowered. The severely hearing-impaired group was the only one to raise F2 in /ae/, but even with that considered, the adults with profound hearing loss are different from all others in their display of F2 raising for /i/ and /I/. Range of percent change is comparable across the adult groups and larger in the children. However, range across individuals with profound and severe hearing loss is more restricted than range across the adults and the children with normal hearing! As groups, it is those subjects with normal hearing who show significant effects of bite block, not those with

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hearing loss. Nevertheless, observations of individuals showed that a majority of individuals in every group showed a significant main effect of bite block on F2, with the high vowels most often affected.

Computer simulation predicted that F1 would be raised for /i/ and /I/ and this was shown very consistently across all groups and all individuals. The only exception was frequent lowering patterns for /I/ in the adults with profound hearing loss. /ae/ F1 moved in both directions in all adult subjects, despite hearing status. The children were the only subjects who consistently lowered F1 as a group and as individuals. The 10-mm bite block used with them probably created a less-than-normal interincisal distance for this vowel. Only the group of children showed a significant effect of bite block on /ae/ F1, but at least half, and most often a majority of individual subjects in every group showed a significant main effect of bite block on F1, with a trend for /ae/ to be most affected.

Masking Effects

Observations here are drawn from Tables 10.5 and 10.29.

The masking condition lowered F2 in the group, but the change was not statistically significant. F2 was lowered in a majority of the individual subjects and the change was significant. Masking effects mirrored bite-block effects for /i/ and /I/.

F1 was raised for /i/ and /I/ in the masking condition. Results were not statistically significant for the group, but were for a majority of the individuals. Masking effects mirrored bite-block effects for /i/ and /I/. /ae/ F1 appeared to be particularly affected by this condition.

In comparing masking effects across all subject groups and individuals, it is noted that the children showed no significant effects of masking on F2, but a majority of adults within every subject group, regardless of hearing status, did! With F1, on the other hand, the individual children and the individual adults with normal hearing and with severe hearing loss showed a main effect of masking, but the profoundly hearing-impaired did

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not, perhaps, as speculated in the previous chapter, because jaw height may be monitored visually and kinesthetically. Also, in all three groups of adults, the masking changes largely followed bite-block changes. That is, the bite block condition and the masking condition each produced a lowered F2 and a raised F1 in the adults with normal hearing, a pattern of raising of F2 and F1 change in both directions for the adults with profound hearing loss. and identical effects for /i/ and /I/ in the severely hearing-impaired.

Bite-Block-and-Masking Interaction

Observations here are drawn from Tables 10.6 and 10.30.

The bite-block-plus-masking condition lowered F2. The changes were significant for /i/ and /I/ in the group. Half of the individual subjects exhibited a significant effect of bite block and masking, but post hoc testing revealed individual variation, with some individuals most affected by the combined condition and others least affected by it.

F1 was raised in /i/ and /I/, but lowered in /ae/. The effect was statistically significant for /i/ in the group. Half of the individual subjects showed a significant bite-block and masking interaction, but post hoc tests revealed no prevailing pattern of change.

Comparing across subject groups and individuals, the adults with severe hearing loss are more like the adults and the children with normal hearing than the adults with profound hearing loss. They are alike in that F2 was lowered for every vowel, while the adults with profound hearing loss exhibited a pattern of raising F2 for the high vowels. They are also alike in that the groups all showed significant lowering of F2 in two or more vowels, but the profoundly hearing-impaired showed no significant effects. While there is some similarity of direction of change in F1 across the subject groups, all except the adults with profound hearing loss exhibited a significant effect of the bite-block-plus-masking condition on at least one vowel.

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Variability

Observations here are drawn from Tables 10.7-10.9 and 10.31.

No effects of bite block, masking, or bite-block-plus-masking on variability were shown for the adults with severe hearing loss, as individuals or as a group. These were the only subjects who did not display such changes. The group of adults with normal hearing showed a significant effect of bite block on /ae/ F2 variability. Half of the children showed a significant effect of bite block on F2 variability, collapsed across vowels. The adults with profound hearing loss showed the most changes in variability. The group displayed an effect of bite block on /i/ and /ae/ F1 standard deviation, an effect of bite-block-plus-masking on /ae/ F1 variability and a majority of individuals showed a main effect of bite block on F1 standard deviation, collapsed across vowels.

Discussion of and Conclusions Drawn from These Results

It may be concluded from these results that articulatory compensation for a bite block by adults with severe hearing loss is substantial and immediate, as it is with adults with normal hearing, but not complete, yielding small changes. Again, the practical implications of these changes were not tested. That is, it is not known if the changes measured acoustically would affect vowel category assignment by listeners.

It must also be concluded that auditory feedback plays a role in articulatory compensation, given that these participants exhibited more significant change in the bite-block-plus-masking condition than in any other.

The theoretical implication is that compensatory skill is also an attribute of articulatory systems wherein articulatory targets are auditory, but based on information that is diminished and/or distorted. Also, given time, subjects might better compensate for a bite block with practice. The hypotheses that adults with severe hearing loss compensate for a bite block, as seen in adults with normal hearing, and that auditory feedback plays a role in this compensation are both accepted.

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CHAPTER ELEVEN

INTENSITY, F0, AND PRACTICE EFFECTS

In addition to the F2 and F1 measurements reported in Chapters 7 through 10, intensity (RMS amplitude) and fundamental frequency measurements were also made for every token in every condition to monitor voice source attributes. Mean RMS amplitude values in decibels and mean F0 values in Hertz are recorded in Tables 11.1 - 11.4 for every vowel in every condition and for each subject (for whom there were data) in each of the four groups, respectively. Thus each subject typically contributed 24 mean values, 12 of each of F0 and dB. In addition, the standard deviation values for each mean were also used as raw data (24 values). These are also recorded in Tables 11.1 - 11.4. Repeated measures, two-way ANOVAs (for Group and Condition) were conducted for dB, F0, dB standard deviation, and F0 standard deviation measurements across all four subject groups. The repeated measures ANOVAs were performed separately for each vowel, because there were missing data for subjects within every group except the adults with profound hearing loss. For them, additional repeated measures, two-way ANOVAs (for Vowel and Condition) were performed. Those F tables and subsequent post hoc results may be found in Appendix G. All other F tables and post hoc results are presented in this chapter in Tables 11.5 - 11.12.

Intensity

A main effect of condition on intensity (RMS amplitude) was found for every vowel. (See Table 11.5.) Post hoc Least Significant Difference (LSD) comparisons were performed and are summarized in Table 11.7. The findings for each vowel were consistent.

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Table 11.1.--Intensity, F0, and Standard Deviation Measurements for Adults with Normal Hearing

Subject	Vowel	Condition	dB	F0	dB SD	F0 SD
N1M	/i/	Normal	40.83	113.75	1.85	5.15
N1M	/i/	Bite Block	47.43	122.64	1.99	10.65
N1M	/i/	BiteBl & Mskng	43.08	111.23	2.33	4.75
N1M	/i/	Masking	43.18	117.00	2.04	3.00
N1M	/I/	Normal	44.56	116.13	1.41	4.15
N1M	/I/	Bite Block	47.63	127.63	2.28	10.69
N1M	/I/	BiteBl & Mskng	46.25	117.31	2.32	9.37
N1M	/I/	Masking	44.38	120.56	1.67	6.23
N1M	/ae/	Normal	43.14	108.29	2.32	3.36
N1M	/ae/	Bite Block	45.87	104.87	2.88	7.88
N1M	/ae/	BiteBl & Mskng	47.60	111.00	2.67	7.30
N1M	/ae/	Masking	44.31	113.13	2.41	4.41
N2F	/i/	Normal	36.60	249.00	1.30	10.15
N2F	/i/	Bite Block	44.46	274.69	2.37	19.44
N2F	/i/	BiteBl & Mskng	44.36	278.07	3.18	15.05
N2F	/i/	Masking	38.44	254.56	1.37	5.57
N2F	/I/	Normal	N/A	N/A	N/A	N/A
N2F	/I/	Bite Block	N/A	N/A	N/A	N/A
N2F	/I/	BiteBl & Mskng	N/A	N/A	N/A	N/A
N2F	/I/	Masking	N/A	N/A	N/A	N/A
N2F	/ae/	Normal	44.06	227.94	2.35	10.72
N2F	/ae/	Bite Block	51.23	251.00	2.35	20.67
N2F	/ae/	BiteBl & Mskng	54.25	256.31	1.95	12.35
N2F	/ae/	Masking	48.87	229.80	1.89	4.77
N3M	/i/	Normal	43.63	135.44	4.57	26.11
N3M	/i/	Bite Block	45.94	156.44	3.21	17.08
N3M	/i/	BiteBl & Mskng	48.13	165.07	5.25	25.35
N3M	/i/	Masking	44.07	142.93	3.77	20.70
N3M	/I/	Normal	45.13	135.50	2.92	11.01
N3M	/I/	Bite Block	47.88	157.19	2.63	9.84
N3M	/I/	BiteBl & Mskng	51.71	169.06	4.07	10.49
N3M	/I/	Masking	47.06	144.69	4.81	20.39
N3M	/ae/	Normal	43.56	122.75	3.05	12.96
N3M	/ae/	Bite Block	45.31	141.88	2.52	8.12
N3M	/ae/	BiteBl & Mskng	50.35	150.24	3.87	22.18
N3M	/ae/	Masking	47.50	128.13	3.52	16.95

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Subject	Vowel	Condition	dB	F0	dB SD	F0 SD
N4F	/i/	Normal	42.00	220.00	1.75	7.10
N4F	/i/	Bite Block	41.13	213.88	3.28	15.25
N4F	/i/	BiteBl & Mskng	45.80	234.67	5.23	13.65
N4F	/i/	Masking	45.33	226.00	2.77	4.47
N4F	/I/	Normal	44.13	224.38	1.71	7.44
N4F	/I/	Bite Block	43.50	214.38	2.13	15.82
N4F	/I/	BiteBl & Mskng	48.63	236.63	2.34	8.87
N4F	/I/	Masking	49.31	231.06	2.60	7.84
N4F	/ae/	Normal	47.47	196.47	1.94	8.75
N4F	/ae/	Bite Block	45.44	194.63	3.18	13.08
N4F	/ae/	BiteBl & Mskng	51.13	212.53	2.00	5.72
N4F	/ae/	Masking	51.25	211.19	1.44	5.09
N5M	/i/	Normal	N/A	N/A	N/A	N/A
N5M	/i/	Bite Block	N/A	N/A	N/A	N/A
N5M	/i/	BiteBl & Mskng	N/A	N/A	N/A	N/A
N5M	/i/	Masking	N/A	N/A	N/A	N/A
N5M	/I/	Normal	41.60	141.40	2.95	7.98
N5M	/I/	Bite Block	44.88	152.00	2.53	9.47
N5M	/I/	BiteBl & Mskng	50.38	152.19	2.90	12.02
N5M	/I/	Masking	49.06	151.00	1.77	9.24
N5M	/ae/	Normal	43.06	130.63	2.29	5.08
N5M	/ae/	Bite Block	46.69	136.75	2.12	3.99
N5M	/ae/	BiteBl & Mskng	51.56	137.88	1.83	6.62
N5M	/ae/	Masking	49.25	133.19	1.98	4.97
N6M	/i/	Normal	30.50	130.63	1.21	6.43
N6M	/i/	Bite Block	31.63	128.63	1.75	6.78
N6M	/i/	BiteBl & Mskng	40.53	152.13	2.59	6.87
N6M	/i/	Masking	37.81	150.88	3.67	5.14
N6M	/I/	Normal	31.25	129.56	1.57	6.31
N6M	/I/	Bite Block	32.56	131.00	2.78	5.81
N6M	/I/	BiteBl & Mskng	43.20	153.47	1.94	6.64
N6M	/I/	Masking	38.38	150.50	2.68	4.28
N6M	/ae/	Normal	37.50	122.50	1.79	6.34
N6M	/ae/	Bite Block	34.44	124.19	3.41	3.67
N6M	/ae/	BiteBl & Mskng	45.81	148.50	1.91	7.87
N6M	/ae/	Masking	44.19	143.19	1.94	5.60

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Table 11.2.--Intensity, F0, and Standard Deviation Measurements for Children with Normal Hearing

Subject	Vowel	Condition	dB	F0	dB SD	F0 SD
C1F	/i/	Normal	40.78	339.73	3.92	24.86
C1F	/i/	Bite Block	40.77	343.50	3.20	18.50
C1F	/i/	BiteBl & Msknq	46.72	433.89	5.33	34.16
C1F	/i/	Masking	N/A	N/A	N/A	N/A
C1F	/I/	Normal	44.35	366.10	4.59	68.45
C1F	/I/	Bite Block	47.20	350.25	2.19	46.38
C1F	/I/	BiteBl & Msknq	48.12	446.90	4.59	38.79
C1F	/I/	Masking	47.68	463.08	3.20	58.32
C1F	/ae/	Normal	46.20	326.33	5.99	33.16
C1F	/ae/	Bite Block	47.06	318.00	4.36	32.26
C1F	/ae/	BiteBl & Msknq	48.50	389.93	2.69	36.39
C1F	/ae/	Masking	50.28	425.11	1.60	30.85
C2M	/i/	Normal	41.38	288.13	1.68	10.47
C2M	/i/	Bite Block	40.78	346.89	5.05	28.37
C2M	/i/	BiteBl & Msknq	44.92	414.46	3.01	28.49
C2M	/i/	Masking	43.35	407.44	3.73	44.16
C2M	/I/	Normal	46.01	276.86	4.31	39.12
C2M	/I/	Bite Block	45.25	365.33	3.54	18.37
C2M	/I/	BiteBl & Msknq	48.56	394.00	2.43	21.30
C2M	/I/	Masking	46.28	377.00	3.53	40.77
C2M	/ae/	Normal	49.21	261.10	3.47	10.41
C2M	/ae/	Bite Block	48.15	342.00	3.52	29.45
C2M	/ae/	BiteBl & Msknq	51.35	385.46	3.44	50.57
C2M	/ae/	Masking	49.03	343.86	3.60	37.19
C3F	/i/	Normal	41.98	379.33	10.80	64.28
C3F	/i/	Bite Block	42.62	341.22	6.04	54.86
C3F	/i/	BiteBl & Msknq	43.13	362.00	6.38	80.49
C3F	/i/	Masking	46.88	477.13	8.96	56.82
C3F	/I/	Normal	41.28	397.60	7.34	72.02
C3F	/I/	Bite Block	42.47	340.33	6.61	88.65
C3F	/I/	BiteBl & Msknq	46.07	342.27	6.78	85.08
C3F	/I/	Masking	45.26	439.83	4.52	96.34
C3F	/ae/	Normal	45.22	351.31	5.55	87.17
C3F	/ae/	Bite Block	44.67	319.83	4.29	58.62
C3F	/ae/	BiteBl & Msknq	49.76	346.00	5.85	71.28
C3F	/ae/	Masking	47.07	385.94	4.36	83.43

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Subject	Vowel	Condition	dB	F0	dB_SD	F0_SD
C4M	/i/	Normal	46.95	296.21	5.28	23.49
C4M	/i/	Bite Block	46.79	279.20	5.31	13.94
C4M	/i/	BiteBl & Mskng	48.95	295.88	3.94	11.87
C4M	/i/	Masking	47.00	311.93	3.55	21.17
C4M	/I/	Normal	52.44	300.69	4.97	40.15
C4M	/I/	Bite Block	47.38	252.07	5.77	19.11
C4M	/I/	BiteBl & Mskng	47.91	279.46	4.26	26.41
C4M	/I/	Masking	48.88	290.69	2.90	23.51
C4M	/ae/	Normal	51.33	263.20	2.95	18.50
C4M	/ae/	Bite Block	48.95	244.13	2.91	12.47
C4M	/ae/	BiteBl & Mskng	N/A	N/A	N/A	N/A
C4M	/ae/	Masking	51.39	270.50	2.61	19.40
C5M	/i/	Normal	39.10	321.00	4.00	21.30
C5M	/i/	Bite Block	41.66	307.00	2.83	57.70
C5M	/i/	BiteBl & Mskng	47.52	329.00	2.91	8.21
C5M	/i/	Masking	49.10	320.00	3.95	17.10
C5M	/I/	Normal	44.22	252.93	4.58	22.92
C5M	/I/	Bite Block	47.31	269.00	3.33	12.02
C5M	/I/	BiteBl & Mskng	47.05	331.20	4.16	13.37
C5M	/I/	Masking	45.94	313.57	4.37	20.36
C5M	/ae/	Normal	44.37	289.15	6.81	21.86
C5M	/ae/	Bite Block	49.88	346.10	2.93	35.83
C5M	/ae/	BiteBl & Mskng	51.47	335.00	4.50	35.01
C5M	/ae/	Masking	49.85	378.60	4.43	50.43
C6F	/i/	Normal	45.45	391.78	4.91	30.80
C6F	/i/	Bite Block	45.45	391.31	6.31	24.49
C6F	/i/	BiteBl & Mskng	46.80	372.08	4.05	26.15
C6F	/i/	Masking	46.36	381.09	4.25	41.33
C6F	/I/	Normal	50.69	396.79	4.33	40.90
C6F	/I/	Bite Block	48.77	370.39	4.15	28.54
C6F	/I/	BiteBl & Mskng	49.46	362.13	5.12	19.13
C6F	/I/	Masking	46.02	373.93	3.99	44.04
C6F	/ae/	Normal	50.06	361.44	5.74	43.48
C6F	/ae/	Bite Block	46.67	338.44	5.16	34.05
C6F	/ae/	BiteBl & Mskng	47.54	342.20	5.43	24.55
C6F	/ae/	Masking	49.68	349.64	3.78	24.98

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Table 11.3.--Intensity, F0, and Standard Deviation Measurements for Adults with Profound Hearing Loss

Subject	Vowel	Condition	dB	F0	dB SD	F0 SD
P1M	/i/	Normal	43.38	183.13	2.66	15.83
P1M	/i/	Bite Block	47.17	200.58	2.95	17.12
P1M	/i/	BiteBl & Mskng	51.00	204.82	2.83	13.56
P1M	/i/	Masking	40.91	176.64	4.25	15.38
P1M	/I/	Normal	48.31	214.13	3.38	5.84
P1M	/I/	Bite Block	53.00	233.07	2.83	12.67
P1M	/I/	BiteBl & Mskng	53.33	226.17	1.72	22.97
P1M	/I/	Masking	47.89	218.78	2.93	12.83
P1M	/ae/	Normal	45.06	156.31	1.77	19.54
P1M	/ae/	Bite Block	51.85	166.85	2.41	11.12
P1M	/ae/	BiteBl & Mskng	55.38	166.06	1.41	18.94
P1M	/ae/	Masking	47.00	166.53	2.07	13.04
P2F	/i/	Normal	47.06	200.88	2.05	20.32
P2F	/i/	Bite Block	47.82	166.94	2.40	21.09
P2F	/i/	BiteBl & Mskng	49.63	214.38	2.55	29.47
P2F	/i/	Masking	45.06	180.56	2.95	26.90
P2F	/I/	Normal	45.31	162.63	4.22	9.58
P2F	/I/	Bite Block	42.27	144.67	4.80	16.70
P2F	/I/	BiteBl & Mskng	41.47	153.67	5.26	18.25
P2F	/I/	Masking	40.31	140.00	4.47	20.68
P2F	/ae/	Normal	47.00	155.33	2.49	4.66
P2F	/ae/	Bite Block	51.71	156.64	2.87	7.84
P2F	/ae/	BiteBl & Mskng	45.79	157.36	5.18	16.52
P2F	/ae/	Masking	48.92	152.92	3.64	12.26
P3M	/i/	Normal	47.40	161.40	2.55	7.62
P3M	/i/	Bite Block	48.86	173.50	3.03	13.37
P3M	/i/	BiteBl & Mskng	52.30	192.40	1.34	16.81
P3M	/i/	Masking	53.27	188.00	2.45	8.67
P3M	/I/	Normal	48.36	167.43	2.21	7.26
P3M	/I/	Bite Block	50.00	191.50	2.94	14.83
P3M	/I/	BiteBl & Mskng	53.60	217.73	2.29	20.87
P3M	/I/	Masking	54.40	192.80	0.97	4.44
P3M	/ae/	Normal	50.31	125.90	2.82	11.60
P3M	/ae/	Bite Block	48.92	154.60	2.99	25.08
P3M	/ae/	BiteBl & Mskng	53.36	180.60	2.41	18.05
P3M	/ae/	Masking	54.88	156.40	1.36	13.67

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Subject	Vowel	Condition	dB	F0	dB SD	F0 SD
P4M	/i/	Normal	41.43	130.93	2.21	3.22
P4M	/i/	Bite Block	42.07	135.29	2.70	2.61
P4M	/i/	BiteBl & Mskng	43.00	154.46	3.41	9.98
P4M	/i/	Masking	40.55	131.00	1.44	1.34
P4M	/I/	Normal	42.06	132.19	2.32	3.56
P4M	/I/	Bite Block	42.13	137.06	2.19	5.73
P4M	/I/	BiteBl & Mskng	45.67	155.20	2.94	13.74
P4M	/I/	Masking	43.47	138.93	1.64	7.49
P4M	/ae/	Normal	45.63	119.19	2.00	5.09
P4M	/ae/	Bite Block	51.19	134.69	2.69	6.67
P4M	/ae/	BiteBl & Mskng	51.21	148.00	1.89	11.58
P4M	/ae/	Masking	47.94	128.06	2.11	3.36
P5F	/i/	Normal	43.13	251.13	0.99	8.03
P5F	/i/	Bite Block	42.78	255.44	2.73	6.52
P5F	/i/	BiteBl & Mskng	44.77	265.31	1.83	9.79
P5F	/i/	Masking	45.00	259.75	3.22	6.38
P5F	/I/	Normal	46.08	252.58	1.44	10.63
P5F	/I/	Bite Block	46.57	256.50	1.95	8.26
P5F	/I/	BiteBl & Mskng	48.00	271.44	2.35	8.92
P5F	/I/	Masking	48.69	257.46	1.93	4.25
P5F	/ae/	Normal	51.47	187.53	2.00	7.92
P5F	/ae/	Bite Block	50.47	199.87	2.59	5.76
P5F	/ae/	BiteBl & Mskng	55.44	204.81	2.13	6.79
P5F	/ae/	Masking	55.14	188.50	1.41	4.62
P6M	/i/	Normal	46.44	185.69	1.97	9.10
P6M	/i/	Bite Block	47.20	205.27	1.78	13.56
P6M	/i/	BiteBl & Mskng	49.47	194.67	1.64	15.69
P6M	/i/	Masking	46.31	190.19	2.06	9.99
P6M	/I/	Normal	44.14	144.57	1.66	9.20
P6M	/I/	Bite Block	46.94	151.94	2.38	8.33
P6M	/I/	BiteBl & Mskng	49.69	152.75	1.66	15.72
P6M	/I/	Masking	46.00	150.69	1.71	9.66
P6M	/ae/	Normal	48.25	131.56	2.86	8.25
P6M	/ae/	Bite Block	52.69	143.69	1.08	6.59
P6M	/ae/	BiteBl & Mskng	53.53	161.33	2.13	12.31
P6M	/ae/	Masking	52.00	146.81	1.41	5.89

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Table 11.4.--Intensity, F0, and Standard Deviation Measurements for Adults with Severe Hearing Loss

Subject	Vowel	Condition	dB	F0	dB SD	F0 SD
S1M	/i/	Normal	41.85	127.92	1.07	4.33
S1M	/i/	Bite Block	45.06	165.19	1.34	6.24
S1M	/i/	BiteBl & Msknq	45.33	169.93	1.84	3.03
S1M	/i/	Masking	43.23	161.15	1.54	5.49
S1M	/I/	Normal	44.06	125.75	1.44	3.96
S1M	/I/	Bite Block	50.00	162.31	1.63	4.00
S1M	/I/	BiteBl & Msknq	51.81	168.81	1.64	5.62
S1M	/I/	Masking	49.13	161.69	1.54	6.89
S1M	/ae/	Normal	46.44	116.44	2.31	5.88
S1M	/ae/	Bite Block	52.93	146.27	1.67	5.57
S1M	/ae/	BiteBl & Msknq	52.31	154.44	2.12	6.14
S1M	/ae/	Masking	51.69	149.56	1.25	5.90
S2M	/i/	Normal	42.80	133.27	2.43	5.39
S2M	/i/	Bite Block	49.31	128.75	2.02	9.75
S2M	/i/	BiteBl & Msknq	49.44	124.44	2.25	13.22
S2M	/i/	Masking	43.82	127.18	1.94	5.26
S2M	/I/	Normal	45.63	124.75	2.87	3.64
S2M	/I/	Bite Block	52.44	127.31	2.22	8.04
S2M	/I/	BiteBl & Msknq	50.47	134.73	2.10	7.14
S2M	/I/	Masking	47.63	125.31	2.53	5.83
S2M	/ae/	Normal	44.69	115.25	1.66	2.82
S2M	/ae/	Bite Block	45.38	114.13	2.03	5.16
S2M	/ae/	BiteBl & Msknq	48.69	120.00	1.74	5.22
S2M	/ae/	Masking	48.00	125.53	1.69	4.73
S3F	/i/	Normal	45.09	253.36	2.26	7.49
S3F	/i/	Bite Block	45.42	246.83	1.31	11.04
S3F	/i/	BiteBl & Msknq	45.07	245.21	1.69	6.39
S3F	/i/	Masking	44.43	243.43	1.91	11.04
S3F	/I/	Normal	45.56	226.00	2.79	9.07
S3F	/I/	Bite Block	N/A	N/A	N/A	N/A
S3F	/I/	BiteBl & Msknq	50.50	227.75	2.67	19.55
S3F	/I/	Masking	47.10	234.30	3.07	13.55
S3F	/ae/	Normal	42.13	195.13	1.73	5.60
S3F	/ae/	Bite Block	45.44	200.63	2.73	16.39
S3F	/ae/	BiteBl & Msknq	46.44	194.19	3.33	13.72
S3F	/ae/	Masking	45.20	195.60	1.86	11.36

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Subject	Vowel	Condition	dB	F0	dB SD	F0 SD
S4M	/i/	Normal	40.31	164.62	2.39	12.26
S4M	/i/	Bite Block	43.50	174.60	2.51	24.15
S4M	/i/	BiteBl & Msknq	43.13	157.00	2.53	15.91
S4M	/i/	Masking	N/A	N/A	N/A	N/A
S4M	/I/	Normal	45.07	145.29	4.21	11.63
S4M	/I/	Bite Block	47.94	159.06	2.14	16.63
S4M	/I/	BiteBl & Msknq	50.50	145.14	2.88	15.82
S4M	/I/	Masking	49.64	146.14	2.21	11.51
S4M	/ae/	Normal	44.75	133.69	3.75	14.49
S4M	/ae/	Bite Block	47.47	135.00	1.85	11.99
S4M	/ae/	BiteBl & Msknq	50.81	123.69	3.62	8.65
S4M	/ae/	Masking	51.75	130.50	1.73	8.82
S5F	/i/	Normal	N/A	N/A	N/A	N/A
S5F	/i/	Bite Block	N/A	N/A	N/A	N/A
S5F	/i/	BiteBl & Msknq	N/A	N/A	N/A	N/A
S5F	/i/	Masking	N/A	N/A	N/A	N/A
S5F	/I/	Normal	46.07	219.80	1.79	14.14
S5F	/I/	Bite Block	47.08	251.00	2.78	16.25
S5F	/I/	BiteBl & Msknq	47.36	249.79	2.44	9.90
S5F	/I/	Masking	47.75	222.88	1.83	6.13
S5F	/ae/	Normal	51.25	181.38	1.91	8.01
S5F	/ae/	Bite Block	52.57	211.43	2.53	13.69
S5F	/ae/	BiteBl & Msknq	51.63	214.00	2.87	8.43
S5F	/ae/	Masking	50.63	194.88	1.86	5.24
S6F	/i/	Normal	41.79	224.86	1.37	5.23
S6F	/i/	Bite Block	42.67	256.53	2.44	13.96
S6F	/i/	BiteBl & Msknq	45.57	254.14	1.55	11.92
S6F	/i/	Masking	40.64	242.43	1.39	16.56
S6F	/I/	Normal	41.88	228.00	1.54	9.72
S6F	/I/	Bite Block	44.87	249.07	2.50	16.06
S6F	/I/	BiteBl & Msknq	47.44	256.06	2.31	31.49
S6F	/I/	Masking	41.88	241.56	2.39	18.97
S6F	/ae/	Normal	45.63	205.06	1.71	5.71
S6F	/ae/	Bite Block	51.25	228.38	2.41	12.49
S6F	/ae/	BiteBl & Msknq	54.31	232.31	2.12	7.77
S6F	/ae/	Masking	48.56	213.63	3.37	20.14

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The mean values in dB were: normal condition /i/ = 42.34, bite-block condition /i/ = 44.29, bite-block-plus-masking condition /i/ = 46.34, masking condition /i/ = 44.13; normal condition /I/ = 44.52, bite-block condition /I/ = 46.24, bite-block-plus-masking condition /I/ = 48.51, masking condition /I/ = 46.58; normal condition /ae/ = 45.98, bite-block condition /ae/ = 48.11, bite-block-plus-masking condition /ae/ = 50.75, masking condition /ae/ = 49.26. If one scans these values visually, it is apparent, as the post hoc tests summarized in Table 11.7 confirm, that the bite-block-plus-masking condition increased intensity the most, significantly differentiating it from both the bite-block and the masking conditions. Production of louder tokens in masking conditions would be expected. However, it will be remembered that a monitoring device was used to discourage subjects from speaking louder in masking and bite-block-plus masking conditions to overcome the 80-dB masking noise delivered through earphones. While the means show a statistically significant increase of from roughly 1 to 5 decibels in these conditions, this would not have been loud enough to substantially change the masking effect of the earphone noise. The conditions employing a bite block probably created a novel and somewhat more stressful production posture that may have contributed to more intense vocal effort. It is not surprising, then, that the combined condition (bite-block-plus-masking) resulted in tokens that were significantly louder than those produced in the other conditions. Even the loudest tokens did not exceed 51 decibels, however, so subjects did not shout over the masking noise. A larger concern was whether these slightly more intense productions also resulted in fundamental frequency changes that might have affected formant frequency measurements, mimicking bite-block effects. F0 measurements will be discussed below.

There was also an effect of group on the intensity of /ae/ tokens. (See Tables 11.5 and 11.8 (post hoc tests).) The adults with profound hearing loss produced louder /ae/ tokens (50.63 dB) than did the adults with normal hearing (46.41 dB), p=.0066. It would be reasonable to expect that individuals with hearing loss might speak louder than those with normal hearing, as evidenced in everyday observations of people with hearing loss.

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The repeated measures, two-way ANOVAs (for Condition and Vowel), conducted just for the adults with profound hearing loss, showed similar findings, in that a main effect of vowel and a main effect of condition were shown for RMS amplitude in dB. (See Appendix G1a.) Post hoc LSD tests of the main effect of vowel on dB indicated that the open vowel /ae/ (50.63 dB) was louder than the two close vowels /i/ (46.08 dB), p=.0067, and /I/ (46.99 dB), p=.0213. Post hoc LSD tests of the main effect of condition showed that the bite-block-plus-masking condition (49.81dB) resulted in louder tokens on average than did the normal condition (46.16 dB), p=.0054.

The findings regarding the variability of intensity (dB SD) are shown in Table 11.6. A main effect of group was found for every vowel. Post hoc LSD tests revealed that the children produced vowels that were significantly more variable in intensity than did any of the three adult groups. (See Table 11.8.) For example, for /ae/, mean dB SD, collapsed across condition, was 2.4 for the adults with normal hearing, 4.37 for the children, 2.32 for the adults with profound hearing loss, and 2.24 for the adults with severe hearing loss. Children's speech production is generally known to be more variable, in a variety of parameters, as they develop greater coordination of the speaking mechanism, so this finding was not surprising.

A main effect of condition was also found for /ae/. (See Table 11.6.) Post hoc LSD tests (See Table 11.7.) showed that for /ae/, dB standard deviation was decreased in the masking condition, collapsed across subjects (Normal Condition = 3.08, Bite-Block Condition = 2.86, Bite-Block-Plus-Masking Condition = 2.98, Masking Condition = 2.43). The masking condition was also found to be significantly different from the bite-block-plus-masking condition because the value of the latter and that of the normal condition were almost equal. While significant, these differences were very small. There were no significant findings for the repeated measures, two-way ANOVAs conducted just for the adults with profound hearing loss. (Appendix G1b.)

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Table 11.5.--Repeated Measures, Two-Way Analysis of Variance: Mean RMS Amplitude in dB for All Subjects

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Heat					
Group	212.40	3	70.80	2.13	.1370
Error	532.75	16	33.30		
Condition	157.04	3	52.35	11.58	.0000★★
Error	216.89	48	4.52		
Group, Cond	55.91	9	6.21	1.37	.2259
Error	216.89	48	4.52		
Hit					
Group	100.35	3	33.45	.78	.5198
Error	770.86	18	42.83		
Condition	175.01	3	58.34	14.06	.0000★★
Error	224.10	54	4.15		
Group, Cond	67.84	9	7.54	1.82	.0864
Error	224.10	54	4.15		
Hat					
Group	215.98	3	71.99	3.14	.0496★
Error	436.14	19	22.95		
Condition	277.45	3	92.48	20.22	.0000★★
Error	260.76	57	4.57		
Group, Cond	51.35	9	5.71	1.25	.2857
Error	260.76	57	4.57		

★★ = $p<.01$, ★ = $p<.05$

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Table 11.6.--Repeated Measures, Two-Way Analysis of Variance: Mean Standard Deviation of RMS Amplitude in dB for All Subjects

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Heat					
Group	101.54	3	33.85	7.02	.0032★★
Error	77.12	16	4.82		
Condition	.40	3	.13	.16	.9222
Error	40.00	48	.83		
Group, Cond	12.55	9	1.39	1.67	.1216
Error	40.00	48	.83		
Hit					
Group	67.18	3	22.39	7.42	.0019★★
Error	54.30	18	3.02		
Condition	1.61	3	.54	1.15	.3380
Error	25.24	54	.47		
Group, Cond	5.61	9	.62	1.33	.2415
Error	25.24	54	.47		
Hat					
Group	66.27	3	22.09	17.94	.0000★★
Error	23.40	19	1.23		
Condition	5.60	3	1.87	3.34	.0254★
Error	31.83	57	.56		
Group, Cond	8.80	9	.98	1.75	.0985
Error	31.83	57	.56		

★★ = $p<.01$, ★ = $p<.05$

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Table 11.7.--Summary of Results of Post Hoc Tests of the Main Effect of Condition on RMS Amplitude in dB and dB SD Across All Subjects

	/i/	/ɪ/	/æ/
N vs. BB	↑ ★★	↑ ★★	↑ ★★
N vs. B+M	↑ ★★	↑ ★★	↑ ★★
N vs. M	↑ ★	↑ ★★	↑ ★★
BB vs. B+M	★★	★★	★★
BB vs. M			
B+M vs. M	★★	★★	★

	/i/	/ɪ/	/æ/
N vs. BB			
N vs. B+M			
N vs. M			↓ ★★
BB vs. B+M			
BB vs. M			
B+M vs. M			★

★★= p<.01, ★=p<.05; ↑ = increased RMS amplitude or variability, ↓ = decreased RMS amplitude or variability

Table 11.8.--Summary of Results of Post Hoc Tests of the Main Effect of Group on RMS Amplitude in dB and dB SD Across All Conditions

	/i/	/ɪ/	/æ/
(ANH) vs. (CNH)			
(ANH) vs. (APHL)			★★
(ANH) vs. (ASHL)			
(CNH) vs. (APHL)			
(CNH) vs. (ASHL)			
(APHL) vs. (ASHL)			

	/i/	/ɪ/	/æ/
(ANH) vs. (CNH)	★★	★★	★★
(ANH) vs. (APHL)			
(ANH) vs. (ASHL)			
(CNH) vs. (APHL)	★★	★★	★★
(CNH) vs. (ASHL)	★★	★★	★★
(APHL) vs. (ASHL)			

★★ = p<.01, ★ = p<.05; ANH = adults with normal hearing, CNH = children with normal hearing, APHL = adults with profound hearing loss, ASHL = adults with severe hearing loss

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Fundamental Frequency

A significant ($p<.01$) main effect of group was found for F0 for every vowel, as would be expected. (See Table 11.9.) Post Hoc Tukey LSD tests revealed that the children's high fundamental frequency differed significantly from that of each of the adult groups, but the adult groups were all comparable. (See Table 11.12.)

A significant main effect of condition was also found for F0 for every vowel. (See Table 11.9.) Post hoc LSD tests of the main effect of condition, summarized in Table 11.11, showed that across all subjects, fundamental frequency was raised significantly for the bite-block condition of /ae/. For /I/, F0 in the bite-block-plus-masking condition differed significantly from the bite-block condition because the latter resulted in almost no change in F0 from the normal condition. For example, the mean F0 values across all subjects for the vowel /I/ in the four conditions were: Normal Condition = 207 Hz, Bite-Block Condition = 214 Hz, Bite-Block-Plus-Masking Condition = 228 Hz, and Masking Condition = 225 Hz. There were no significant findings for the bite-block condition of /ae/. It will be remembered from the previous section that a main effect of condition had been found for intensity, and that the bite-block condition significantly increased intensity in every vowel. (See Table 11.7.) However, the bite-block condition significantly raised F0 only for /ae/. Therefore, although /i/ and /I/ tokens spoken in the bite-block condition were significantly more intense than those spoken in the normal condition, the finding of no effect of bite block on F0 suggests that there was not a significant concomitant raising of voice frequency for those two vowels, which may occur as a natural consequence of producing a louder voice. The finding of no significant voice frequency change for the high vowels validates the bite-block findings for /i/ and /I/ reported in Chapters 7 - 10. The change in formant frequencies in bite-block conditions for those vowels cannot be attributed to a fundamental frequency change, lending validity to the claim that the changes were a consequence of the bite-block effect on jaw position. As for /ae/, where F0 was significantly raised, it must be remembered that the adults with normal hearing, the children

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with normal hearing, and the adults with profound hearing loss all showed a lowering of F2 for /ae/, and the children with normal hearing and the adults with profound hearing loss showed a lowering of F1 for /ae/, the opposite direction of a formant-raising change that might be expected simply from a raising of F0. The adults with severe hearing loss did show a raised /ae/ F2 and F1, but this direction of change was limited to that one vowel in one group, who also showed lowering of F2 for the other vowels, and none of these changes was significant. (See Table 10.4.)

Post hoc LSD tests of the main effect of condition, summarized in Table 11.11, also showed that across all subjects, fundamental frequency was raised significantly in the masking condition for all vowels. It will be remembered that post hoc tests had also shown that the masking condition resulted in significantly louder productions of each vowel. (See Table 11.7.) In other words, tokens produced in masking conditions were both more intense and higher in frequency. Changes at the voice source could, then, be offered as a cause for raised formant frequencies in masking conditions. However, a review of Table 10.5 showed that the adults with normal hearing and the adults with severe hearing loss exhibited a lowered F2 across all three vowels in masking conditions. The children with normal hearing also exhibited a lowered F2 in heat and hat in masking conditions. The adults with profound hearing loss had shown a lowered F1 for /I/ and /ae/ and the adults with severe hearing loss also had shown a lowered F1 for /ae/. A raised F0 would actually decrease the probability of making a finding of F2 and F1 lowering, which adds even more validity to these findings. The adults with profound hearing loss exhibited a raised F2 across all vowels and the adults and the children with normal hearing had shown a raised F1 across all vowels. There were also other examples of F2 and F1 raising for specific vowels in some subject groups. Voice source characteristics cannot be ruled out as having contributed to finding F2 and F1 raising in some of these instances. Nevertheless, there is no overall pattern of raised formants in this condition.

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Post hoc LSD tests of the main effect of condition, summarized in Table 11.11, showed that across all subjects, fundamental frequency was raised significantly in the bite-block-plus-masking condition for all vowels, and that the bite-block-plus-masking condition raised /ae/ F0 significantly more than did the bite-block condition. It will be remembered that post hoc tests had also shown that the bite-block-plus-masking condition resulted in significantly louder productions of each vowel (Table 11.7.). Tokens produced in bite-block-plus-masking conditions were both more intense and higher in frequency. Changes at the voice source could, then, be offered as a cause for raised formant frequencies in bite-block-plus-masking conditions. However, a review of Table 10.6 showed that all subject groups except the adults with profound hearing loss, lowered F2 in this condition. Again, a raised F0 would decrease the probability of making a finding of F2 lowering, which adds even more validity to these findings. The adults with profound hearing loss exhibited a raised F2 for /i/ and /I/ and all of the subjects had shown a raised F1 for /i/ and /I/ in this condition. Voice source characteristics cannot be ruled out as having contributed to finding F2 and F1 raising in these instances. However, an overall pattern of F2 lowering for all vowels in three subject groups and a lowering of F2 for /ae/ in the adults with profound hearing loss certainly argue against any suggestion that there was a general pattern of raised formants in this condition.

A significant interaction of Group and Condition was found for /ae/. (See Table 11.9.) Post hoc LSD tests of the interaction revealed one meaningful pattern of change. While all subjects displayed higher F0 values in test conditions compared to the normal condition, all three adult groups displayed the highest mean /ae/ F0 in the bite-block-plus-masking condition. The children, on the other hand, displayed the highest mean /ae/ F0 in the masking condition.

The repeated measures, two-way ANOVA for Vowel and Condition, performed just for the adults with profound hearing loss, showed similar findings. (See Appendix G1c.) A main effect of vowel was shown for F0. F0 in the high vowels /i/ (192 Hz) and /I/ (186

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Hz) was significantly greater than the F0 for /ae/ (158 Hz), p = .0120 and p =.0293, respectively. A main effect of Condition was also shown. (See Appendix G1c.) Collapsed across vowels, the bite-block-plus-masking condition resulted in an F0 (190 Hz) that was significantly greater than that of the normal condition (170 Hz, p = .0005), the masking condition (176 Hz, p = .0063), or the bite-block condition (178 Hz, p = .0190).

Finally, there were no effects of Condition on F0 standard deviation, but there was a main effect of group on F0 SD for every vowel. (See Table 11.10.) Post hoc LSD tests showed that the children exhibited two to four times more variability in fundamental frequency than any of the adult groups, depending upon the vowel. (See Table 11.12.) For example, /ae/ F0 SD was 8.69 for the adults with normal hearing, 41.55 for the children with normal hearing, 10.71 for the adults with profound hearing loss, and 8.91 for the adults with severe hearing loss.

A significant interaction of Group and Condition was found for /I/. (See Table 11.10.) Post hoc LSD tests of the interaction revealed one meaningful pattern of change. While all subjects with hearing loss displayed greater F0 variability in the bite-block-plus-masking condition and the adults with normal hearing showed greatest F0 variability in the bite-block condition, the children displayed greatest variability in the normal condition!

The repeated measures, two-way ANOVA for Vowel and Condition, performed just for the adults with profound hearing loss, showed a main effect of Condition on F0 standard deviation. (See Appendix G1d.) Collapsed across vowels, the bite-block-plus-masking condition resulted in an F0 SD (15.55) that was significantly greater than that of the normal condition (9.29, p = .0008), the masking condition (10.05, p = .0022), or the bite-block condition (11.33, p = .0124).

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Table 11.9.--Repeated Measures, Two-Way Analysis of Variance: Mean F0 for All Subjects

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Heat					
Group	399055.30	3	133018.40	13.01	.0001★★
Error	163631.30	16	10227.00		
Condition	4009.53	3	1336.51	3.26	.0294★
Error	19687.34	48	410.15		
Group, Cond	5482.61	9	609.18	1.49	.1806
Error	19687.34	48	410.15		
Hit					
Group	526287.30	3	175429.10	18.63	.0000★★
Error	169482.00	18	9415.7		
Condition	5997.05	3	1999.02	4.59	.0062★★
Error	23533.07	54	435.80		
Group, Cond	7310.18	9	812.24	1.86	.0777
Error	23533.07	54	435.80		
Hat					
Group	536251.60	3	178750.50	34.14	.0000★★
Error	99489.70	19	5236.30		
Condition	8549.50	3	2849.83	10.43	.0000★★
Error	15571.26	57	273.18		
Group, Cond	6253.28	9	694.81	2.54	.0157★
Error	15571.26	57	273.18		

★★ = $p<.01$, ★ = $p<.05$

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Table 11.10.--Repeated Measures, Two-Way Analysis of Variance: Mean F0 Standard Deviation for All Subjects

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Heat					
Group	7522.79	3	2507.60	5.79	.0070★
Error	6924.09	16	432.80		
Condition	150.95	3	50.32	.84	.4784
Error	2873.31	48	59.86		
Group, Cond	257.06	9	28.56	.48	.8828
Error	2873.31	48	59.86		
Hit					
Group	16171.41	3	5390.47	7.39	.0020★★
Error	13130.19	18	729.46		
Condition	45.41	3	15.14	.50	.6865
Error	1647.70	54	30.51		
Group, Cond	1264.76	9	140.53	4.61	.0002★★
Error	1647.70	54	30.51		
Hat					
Group	16198.24	3	5399.41	15.48	.0000★★
Error	6627.71	19	348.83		
Condition	114.63	3	38.21	.87	.4625
Error	2506.14	57	43.97		
Group, Cond	258.40	9	28.71	.65	.7470
Error	2506.14	57	43.97		

★★ = $p<.01$, ★ = $p<.05$

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Table 11.11.--Summary of Results of Post Hoc Tests of the Main Effect of Condition on F0 and F0 SD Across All Subjects

	/i/	/u/	/ae/
N vs. BB			↑ ★
N vs. B+M	↑ ★★	↑ ★★	↑ ★★
N vs. M	↑ ★	↑ ★★	↑ ★★
BB vs. B+M		★	★
BB vs. M			
B+M vs. M			

F0 SD	/i/	/u/	/ae/
N vs. BB			
N vs. B+M			
N vs. M			
BB vs. B+M			
BB vs. M			
B+M vs. M			

★★= p<.01, ★=p<.05; ↑ = increased F0 or variability, ↓ = decreased F0 or variability

Table 11.12.--Summary of Results of Post Hoc Tests of the Main Effect of Group on F0 and F0 SD Across All Conditions

F0	/i/	/u/	/ae/
(ANH) vs. (CNH)	★★	★★	★★
(ANH) vs. (APHL)			
(ANH) vs. (ASHL)			
(CNH) vs. (APHL)	★★	★★	★★
(CNH) vs. (ASHL)	★★	★★	★★
(APHL) vs. (ASHL)			

F0 SD	/i/	/u/	/ae/
(ANH) vs. (CNH)	★★	★★	★★
(ANH) vs. (APHL)			
(ANH) vs. (ASHL)			
(CNH) vs. (APHL)	★★	★★	★★
(CNH) vs. (ASHL)	★★	★★	★★
(APHL) vs. (ASHL)			

★★ = p<.01, ★ = p<.05; ANH = adults with normal hearing, CNH = children with normal hearing, APHL = adults with profound hearing loss, ASHL = adults with severe hearing loss

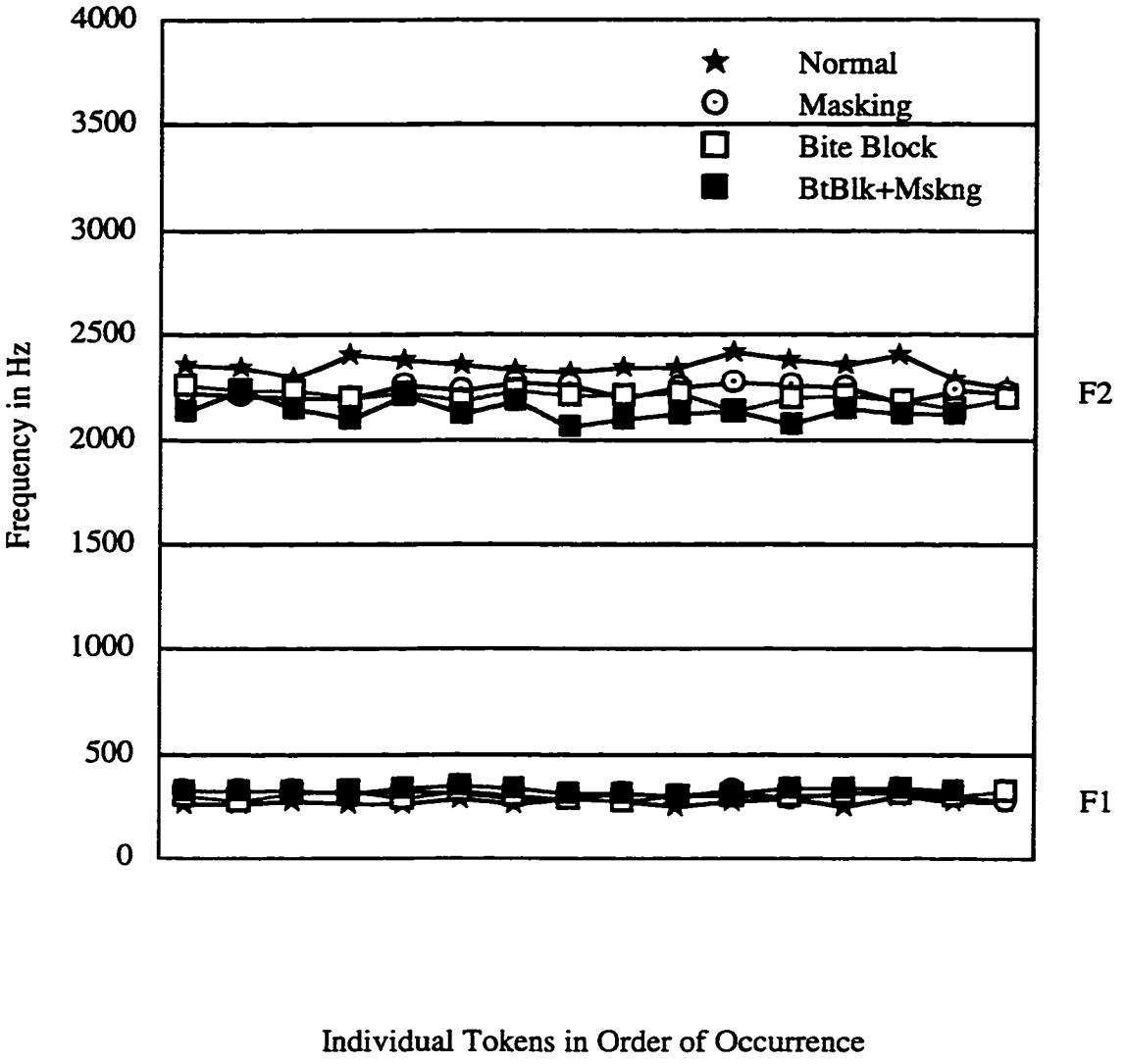
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Practice Effects

A display of each individual token in order of occurrence for every condtion was created for every subject in order to monitor learning effects. These displays consistently showed that there was no substantial learning effect reflected in formant values over the 16 tokens typically produced in every condition. Figures 11.1 - 11.4 are displays selected from one subject from each group for the vowel /i/ to illustrate that there were no substantial practice effects. The number of tokens varied in each condition. It will be remembered that some tokens did not yield measurable F2 and F1 values. Nonetheless, the figures display the exact record of occurrence of usable measures. The displays also clearly illustrate the production variability of the child, C5M. The contrast in the direction of F2 change among subject groups also is reflected by the individual profiles featured here. The F2 raising effect of the bite-block conditions in the adult with profound hearing loss, P3M, contrasts with the F2 lowering effect of the bite-block in the child and the adult with normal hearing, C5M and N6M, and the adult with severe hearing loss, S2M.

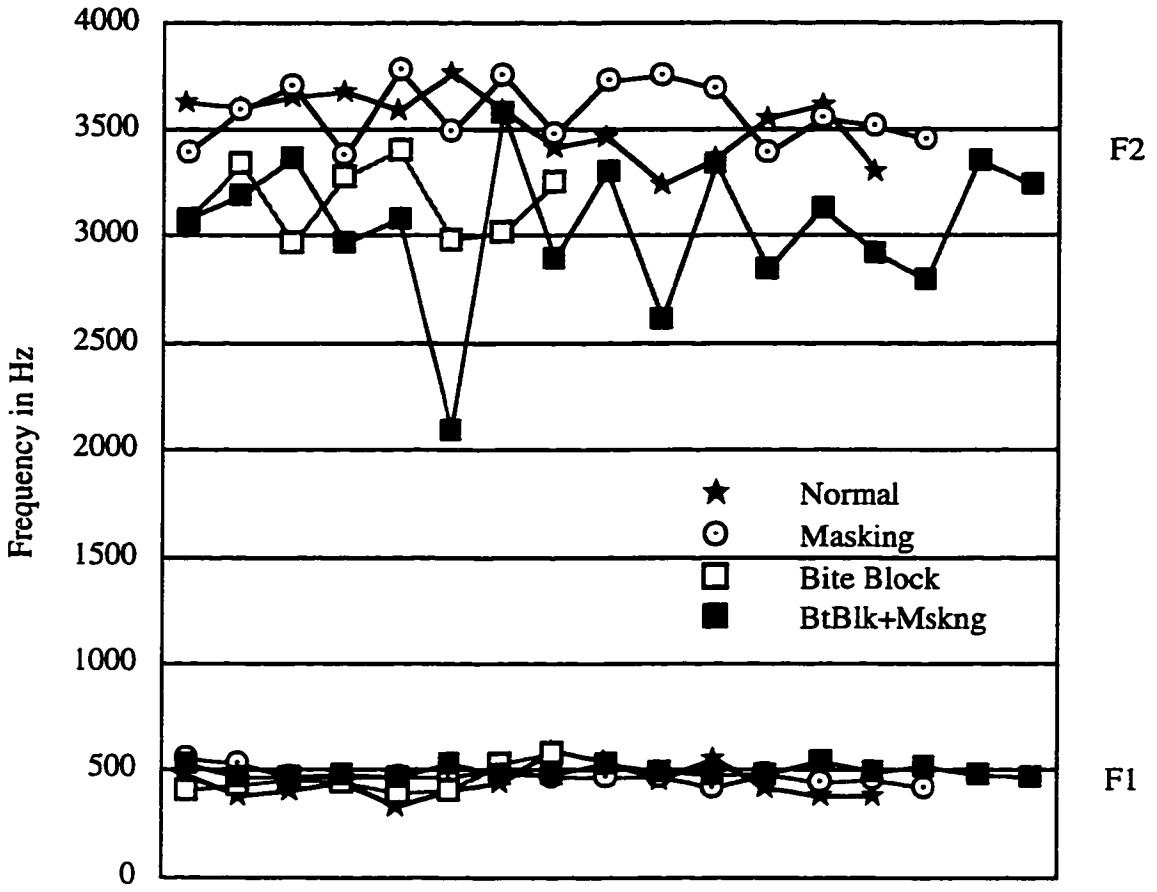
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Fig. 11.1. Subject N6M: Heat Formant Measures for Individual Tokens in Each Condition



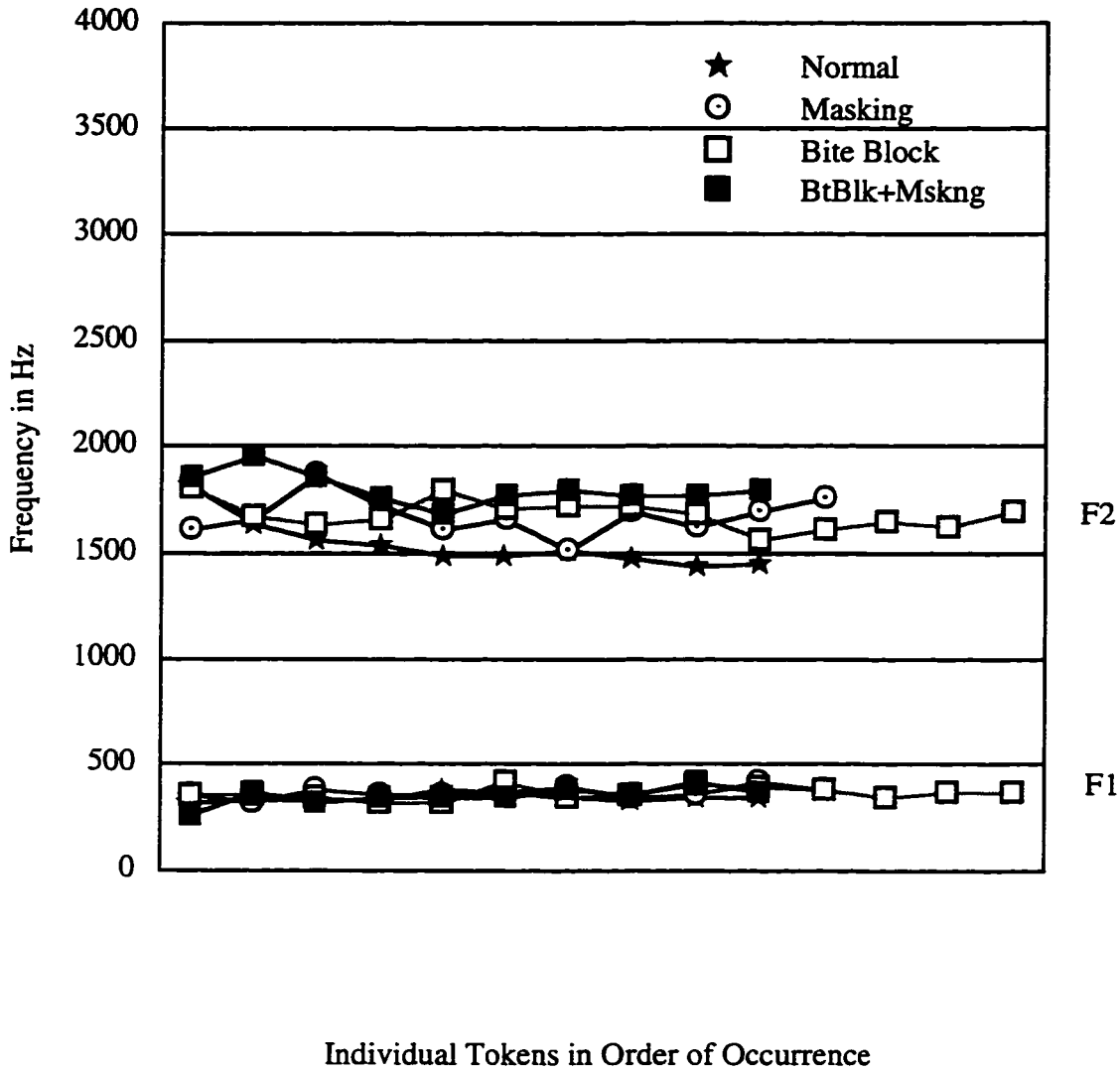
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Fig. 11.2. Subject C5M: Heat Formant Measures for Individual Tokens in Each Condition



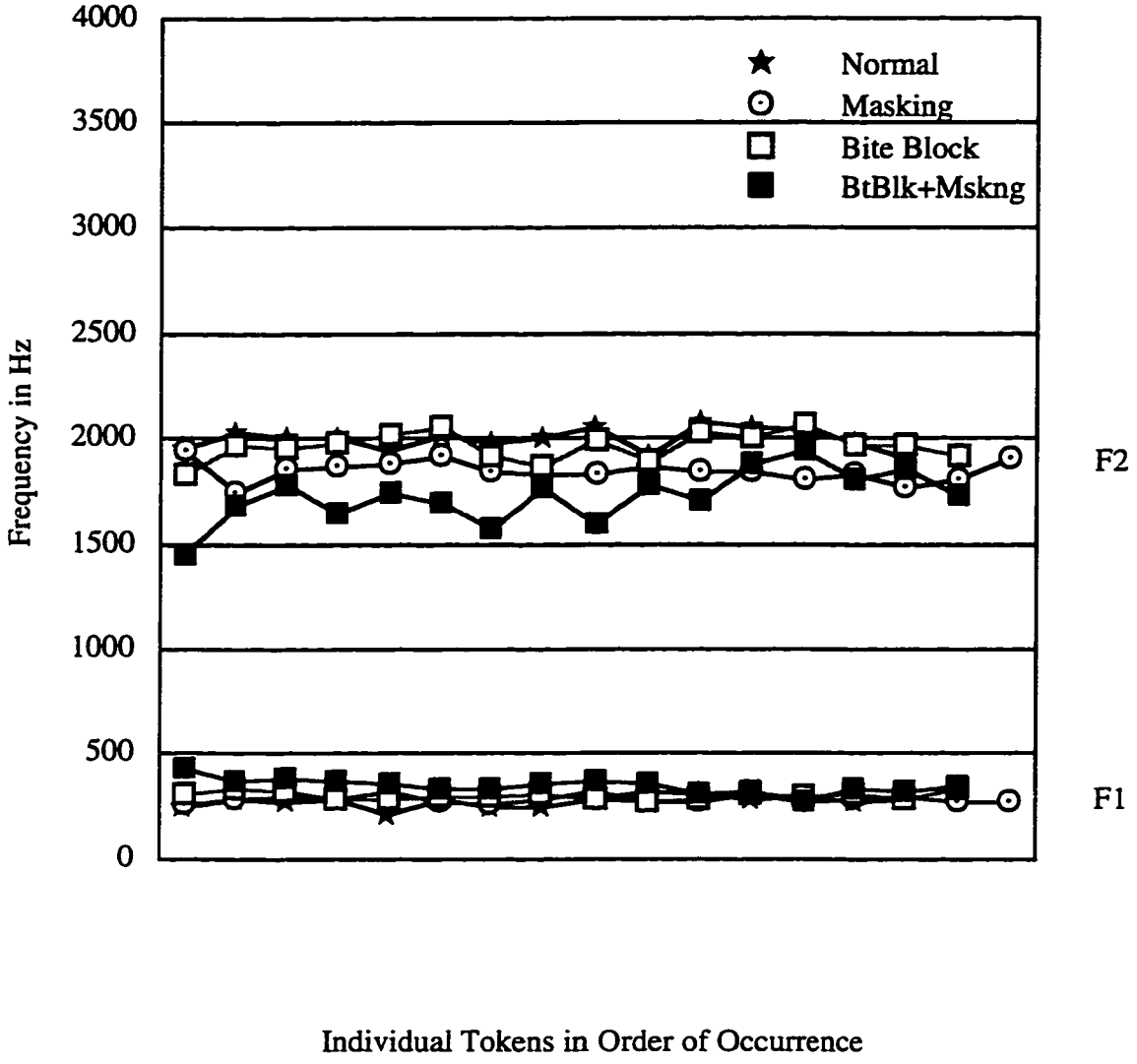
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Fig. 11.3. Subject P3M: Heat Formant Measures for Individual Tokens in Each Condition



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Fig. 11.4. Subject S2M: Heat Formant Measures for Individual Tokens in Each Condition



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Summary of Findings of Intensity, F0 and Practice Effects

While a main effect of condition was found for both intensity and fundamental frequency for every vowel, examination of post hoc results, taken together with direction of formant change for each subject group, largely validated claims regarding test condition effects revealed in formant frequency measurements in Chapters 7 through 10.

Post hoc tests of the main effect of condition showed significant intensity changes for /i/ and /I/ in the bite-block condition, but no corresponding significant F0 change. Thus, while /i/ and /I/ tokens spoken in the bite-block condition displayed increased intensity, they did not exhibit a significant increase in fundamental frequency, validating formant measures indicating changes in the high vowels in the bite-block condition. For /ae/, which showed significant changes in intensity and fundamental frequency, there was a general pattern of lowering of formants, not raising.

Post hoc tests of the main effect of condition showed that both intensity and fundamental frequency were significantly increased in the masking condition. The difference between masking and non-masking conditions was on the order of 1 - 5 dB, so there was little likelihood that subjects overcame the 80 dB masking noise delivered through earphones. Furthermore, the children and the adults with normal hearing, as well as the adults with severe hearing loss, exhibited a lowered F2 in masking conditions, opposite in direction to the effect of a raised F0. While adults with profound hearing loss exhibited a raised F2 in masking conditions, a separate analysis for the profoundly hearing-impaired adults revealed no significant difference between the normal and the masking conditions.

Post hoc tests of the main effect of condition showed that both intensity and fundamental frequency were significantly increased in the bite-block-plus-masking condition. Nonetheless, a general pattern of F2 lowering for all vowels in three subject groups and a lowering of F2 of /ae/ in the adults with profound hearing loss argued against

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any claim that there was an overall pattern of raised formants in this condition due to a raised fundamental frequency.

Finally, no substantial practice effects during test conditions were revealed.

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CHAPTER TWELVE

DISCUSSION

Theoretical Question One: To What Degree Do Adults With Normal Hearing Compensate For A Bite Block And What Is The Role Of Auditory Feedback In This Compensation?

"Chapter One: Introduction and Literature Review" provided a review of a body of literature that suggested that articulatory compensation for a bite block is both complete and immediate. Those studies measured formants at vowel onset and generally found them to be normal or near-normal in bite-block conditions, with little or no practice (Lindblom and Sundberg 1971a, 1971b; Gay and Turvey 1979; Lindblom, Lubker, and Gay 1979; Gay, Lindblom, and Lubker 1981; Kelso and Tuller 1983). Those acoustic studies were supported by Gay, Lindblom, and Lubker's (1981) x-ray data that showed "supershapes" of the tongue, in response to a bite block. Flege, Fletcher, and Homiedan (1988) summed up the findings of that body of literature, with respect to the completeness of compensation, by stating that although a bite block creates a novel speaking situation for talkers, they "have been reported to produce vowels with 'normal' formant frequency values" (p. 212). Kelso and Tuller (1983) summarized those studies' findings about the immediacy of compensation, relating that compensation required little or no practice: "The evidence, then, favors an interpretation that articulatory adjustments to novel contextual conditions created by a bite block are essentially immediate" (p. 218).

However, several more recent studies were also reviewed in "Chapter One". They questioned whether articulatory compensation for a bite block is either complete or immediate (Fowler and Turvey 1980; Flege, Fletcher, and Homiedan 1988; McFarland and Baum 1995; Baum, McFarland, and Diab 1996: Baum, Kim, and Katz 1997). They found

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small, but significant differences between normal and bite-block conditions. McFarland and Baum (1995) also examined individual articulatory profiles and found that some talkers were "good" compensators and some were "imperfect".

Articulatory Compensation

In this investigation the group findings for the adults with normal hearing were that, across vowels, F2 was lowered in the bite-block condition by less than 3%. F1 was raised less than 8%. In "Chapter Four: Computer Simulation of Bite-Block Effects on Formant Frequencies", predictions were made regarding the effect a 20-mm bite block would have on /i/, /I/, and /ae/ if the vocal tract did not compensate for a bite block. The differences from normal formant values were expressed in Hertz. If one expresses the change in absolute Hertz values as percentage differences from normal, the predicted uncompensated percentage change in Hertz would be:

	/i/	/I/	/ae/	/ae/
F2	12% ↓	15% ↓	3% ↓	.3% ↑
F1	103% ↑	95% ↑	5% ↑	.5% ↓

The percentage changes are much greater for the close vowels. Two sets of values are provided for /ae/, the first for an interincisal distance 4 mm more open than normal, and the second for an interincisal distance 1 mm less open than normal. It will be remembered from "Chapter Four" that the direction of change for these latter two sets of values were opposite each other. The obtained values from the group were (See Tables 7.1 a-c.):

	/i/	/I/	/ae/
F2	<3%	<3%	<2%
F1	<8%	<1%	<3%

Clearly, with the exception of /ae/, the group of adults with normal hearing demonstrated considerable compensation for a bite block in the close vowels. The effect of the bite block for /ae/ was expected to be very small, so it is interesting that the percentages indicated that

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for even this small predicted effect, the group of adults with normal hearing did not fully compensate. Nonetheless, for the group, the overall percentage of change was small.

The standard deviation of /ae/ F2 was significantly increased in the bite block condition, suggesting that although the formant was not significantly changed, the bite-block condition caused increased instability in the productions.

Thus the group means and the obtained percent change are consistent with the earlier studies, to the extent that substantial compensation was shown for the close vowels, but the findings are in closest agreement with the later five studies showing substantial, but not fully complete compensation. Indeed, in the case of /i/, F2 was significantly different. Nevertheless, whether this was practically significant was not tested. It is not certain that the changes measured acoustically would affect vowel category assignment by listeners.

Only McFarland and Baum (1995) did an acoustic analysis of individual speakers. They showed individual variability in response to a bite block. Those findings are certainly supported by the results from individual adults with normal hearing in this study. While the bite block changed F2 significantly in all subjects across vowels, the range of percent-change from subject to subject and vowel to vowel was as little as .23% and as large as 16.58%. F2 was lowered in five subjects (imperfect compensation), but raised in N1M, suggesting "over-compensation" on his part. The bite block changed F1 significantly in four subjects, but it was raised for N1M and N2F and lowered for N3M and N5M. Again, the range of percent change was large: .38 to 24.25%. There was also a significant interaction of bite block and vowel for F2 in five of the subjects and for F1 in all of the subjects. However, the results of post hoc tests of these interactions, shown in Table 7.22, indicated variability from subject to subject. In N1M, F2 in the more open vowels /ɪ/ and /ae/ was significantly raised, while in N4F, F2 in the more close vowels /i/ and /ɪ/ was significantly lowered. In N6M the second formant was significantly lowered in all vowels. All subjects showed a significant change in F1 in hat, but F1 was raised in N1M and N2F, and lowered in all of the other subjects.

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While the group average indicated that /ae/ F1 was raised, the majority of individuals showed F1 lowering in bite-block versus non-bite-block conditions. It is believed that the 20-mm bite block created a less-than-normal interincisal distance in these cases. While subjects exhibited the ability to raise the tongue for close vowels in order to compensate for a jaw opened more than usual, they showed less skill at lowering the tongue for an open vowel without the help of the jaw. The predicted changes to /ae/ F1 were no larger than 5%, but the obtained values varied considerably: N1M = <25%, N2F = <19%, N3M = <8%, N4F = <17%, N5M = <1%, N6M = <8%.

Like McFarland and Baum (1995), this study revealed that some subjects were good compensators and others were "imperfect" compensators. A review of Figures 7.21 - 7.23 reveals that N1M was a good compensator. F2 was raised, not lowered, in all vowels. In /I/ this change was significant. Thus N1M was not only compensating, but "over-compensating" for the presence of the bite block. Only /ae/ F1 was significantly raised. (Also see Figure 7.3.) On the other hand, N6M was an imperfect compensator. F2 was significantly lowered in all three vowels. He was the only subject who exhibited significant F1 lowering in /I/. /ae/ F1 was also significantly lowered.

Thus the group and individual results showed substantial, but not complete, compensation. They also showed that compensation, as indicated by changes in F1, was more complete for the high and mid vowels than for /ae/ and that individuals varied in their ability to compensate for a bite block.

"Chapter Eleven: Intensity, F0 and Practice Effects" provided figures that showed that there was no dramatic learning effect over the duration of a condition. That is, initial tokens were not substantially more off the mark than later tokens. Plots were not provided for all 24 subjects nor was the difference between early and late-produced tokens statistically analyzed for any subject. Nevertheless, the approach taken in this investigation has been a conservative one. That is, formant measures were taken at mid-vowel in all cases, not at vowel onset. In addition, means were typically calculated over 16 tokens in

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each condition. Certainly, if there had been an immediate, or even gradual learning effect over a token or several tokens, it is improbable that the differences between the bite-block and normal conditions would have been statistically significant in as many cases as they were. Though compensation may be substantial, depending on vowel target, this evidence points to an interpretation that complete compensation for a bite block is not immediate. Therefore, the initial hypothesis, that adults with normal hearing compensate completely for a bite block, is rejected.

The difference between the general claims of the earlier studies and these results prompted a return to that literature for a closer look. Why have the claims been so long-held that articulatory compensation for a bite block is both complete and immediate? Why is there a discrepancy between the earlier findings and this and the other more recent studies?

One possible reason may lie in the context in which tokens were produced in those studies. Table 12.1 provides details of the production tasks in the earlier studies. The

Table 12.1.--Production Tasks in Early Bite-Block Studies

Lindblom and Sundberg 1971a and b	isolated, sustained vowels
Gay and Turvey 1979	triads of each vowel, isolated
Lindblom, Lubker, and Gay 1979	triads of each vowel, isolated
Gay, Lindblom, and Lubker 1981	triads of each vowel, isolated
Kelso and Tuller 1983	triads of each vowel, isolated, and triads of "a pVp again"

study by Kelso and Tuller (1983) was the only investigation that used vowel tokens in a carrier phrase, but they did not report the acoustic results of the normal condition for every subject, nor the results of a bite-block-only condition. They stated: "Because of the lack of any ***consistent*** (emphasis mine) acoustic change, we have restricted our discussion to normal or auditorily masked speech compared with the most extreme condition of sensory deprivation, omitting the intermediate conditions" (p.220). The other studies instructed

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subjects to produce isolated sustained vowels or isolated vowels in series. In the Lindblom and Sundberg work (1971 a and b) it is not entirely clear if productions of vowels were randomized from token to token. They reported, "Five recordings of all vowels were made in a randomized order" (p.16, 1971a). They may have produced a series of five isolated utterances of each vowel in turn. If interpreted correctly, the Gay and Turvey (1979), Lindblom, Lubker, and Gay (1979), and Gay, Lindblom, and Lubker (1981) investigations used three triads of each vowel. In other words, subjects produced nine isolated utterances of each vowel in series in each condition. In addition, the Gay, Lindblom, and Lubker (1981) acoustic data were obtained from the token used for x-ray data, the last of the third triad (i.e., the ninth token). The Kelso and Tuller (1983) study reported results from the most extreme conditions (bite block plus two forms of anesthetization), but before talkers produced tokens in those extreme conditions, it is implied that all three vowels were produced in three triads, isolated, and in three triads, in a carrier phrase, in a bite-block-only condition before anesthetization. Thus it is inferred that subjects had practice with 54 bite-block utterances (3 vowels x 9 isolated and 9 carrier phrases) before anesthetization conditions from which results were reported. It may be possible that those procedures afforded subjects a great deal more practice, in a minimally varying series, than was given here. The subjects in this study produced completely randomized vowels in a carrier phrase, a more natural speech environment. This may have resulted in less complete compensation for a bite block. Indeed, of the more recent studies that have suggested that compensation is not complete, Fowler and Turvey (1980), though they used isolated vowels, presented them randomly, from a computer screen, in a more demanding timed task and found "a very small, but detectable effect of the bite block on acoustic measures of the vowel" (p. 314). Flege, Fletcher, and Homiedan (1988) and Bohn, Flege, and Dagenai (1991) used carrier phrases and showed palatographic/acoustic incomplete compensation and "selective" rather than "complete" glossometric compensation, respectively. In short, talkers may exhibit more ability to compensate for a

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bite block when given simple, repetitive utterances in series than in more challenging extended speech contexts.

Another possible reason for differences in reported compensation may be the form of the bite block used. All of the studies listed in Table 12.1 used blocks, some acrylic, some notched. This study used a customized bite block of dental impression material, producing a 19- to 20-mm interincisal distance in every adult subject. It may be that the customized bite block reduced variation in placement and the possibilities for jaw translation or rotation to aid compensation.

It may also be the case that the findings from this group of adults with normal hearing do not really differ so greatly from the older reported results, if one reviews the depth of analysis applied to those results, summarized in Table 12.2. Other than the study by Kelso and Tuller (1983), no consistent statistical tests were applied. The quotations suggest some change in bite-block conditions and individual variability. Lindblom, Lubker, and Gay (1979) did some additional examination beyond that described in Table 12.2. They plotted individual tokens by position in the test list. Tokens were compared to +/- 3 standard deviations relative to the mean value of the normal data. "For all the vowels it is evident that the majority of the data points fall inside the rectangles. If successful compensation is said to occur when each formant of a given . . . vowel falls within +/- 3 s of its mean normal value it may be concluded . . . that, on the whole, all of our subjects were successful in compensating for the extreme bite blocks" (p. 154). Three standard deviations allows rather large differences, but even so, their Subject Five did not compensate (fall within +/- 3SDs in the 12 trials), so they gave him a 15-mm bite block and he demonstrated compensation, but this was also after he had received practice with the 22.5-mm bite block.

While Flege, Fletcher, and Homiedan (1988) were speaking about perceptual measures, their statement seems to apply generally to an explanation for the discrepancy between the findings of this and earlier studies: "We believe. . . that distortion has not been

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noted in previous studies examining bite-block vowels because sufficiently sensitive methods have not been applied" (p. 224).

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Table 12.2.--Summary of Analyses Applied to, and Findings of, Early Bite-Block Studies of Adults with Normal Hearing

Study	Form of Analysis	Findings
Lindblom and Sundberg (1971 a and b)	Simple examination of formant measures at first glottal pulse for unspecified number of subjects; provided plot of group means (presumed) for /i/.	"the formant patterns for 5-, 15-, and 25-mm jaw opening approach the normal values within rather narrow limits. The small scatter rules out the possibility of learning effects. Similar observations were made for all other vowels" (p.17, 1971a) "the formant patterns approach the normal values rather closely" (p.1177, 1971b) Close examination of figures reveals an increase of 25 to 50 Hz in F1 with the larger blocks. F2 dropped 50 to 100 Hz with the largest block.
Gay and Turvey (1979)	Simple examination of formant measures at first glottal pulse for one normal token of /i/ from one of the two subjects compared to the formant values in 9 trials in the most extreme condition. No other actual values given.	/a/ was reported as unaffected in any condition and /i/ and /u/ were reported as unaffected by the bite-block condition alone.
Lindblom, Lubker, and Gay (1979)	Formant measures at glottal onset or no later than 30 ms for six adults. Average data in mel units was pooled over six subjects and three formants. Provided individual formant means for the normal condition and the differences in Hz between normal and bite-block conditions.	Range of /i/ F2 differences of bite-bl from normal was 1 to 88 Hz. Range of F1 differences was 0 to 22 Hz for /I/. "by and large, the extreme bite block condition did not prevent our subjects from achieving in most instances close to perfect formant pattern compensation" (p.154). "Systematic deviations from normal formant frequency means were observed in the form of both under- and over-compensation. In general, they were on the average of the order of 25 mels and were judged to be perceptually insignificant or to cause no major problems of contrast" (p.157).

Gay, Lindblom, and Lubker (1981)	Compared formants of ninth token from BB and N conditions.	"although some discrepancies in F patterns between the two conditions exist, they are nowhere so great as to suggest absence of compensatory behavior. Rather, their magnitude does not rule out as possible sources of variability, measurement error and normal variability of production along with slight imprecision in compensation. We concluded from informal listening tests and from the spectrographic measurements that speakers were able to compensate successfully for the bite blocks" (p.803).
Kelso and Tuller (1983)	Measured formants at first glottal pulse of isolated vowels and where F2 reached its most extreme value in the carrier phrase. T-tests for each subject comparing nine normal (or masking) and nine tokens from most extreme conditions only.	Found no significant differences for isolated vowels or targets from carrier phrase, but it is inferred that for some subjects the most extreme conditions were compared to masking, rather than normal, conditions. This may have contributed to a finding of no significant differences.

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Finally, of the more recent studies, only McFarland and Baum (1995) examined individual profiles. The results here are consistent with their findings of variability across subjects in ability to compensate. Thus group results reported in earlier studies may have masked individual variability.

The Role of Auditory Feedback in Articulatory Compensation

It was also hypothesized that auditory feedback plays a role in compensation for a bite block. Tables 7.6 and 7.9 summarized the findings for the group of adults with normal hearing from the bite-block-plus-masking condition. The tables provide considerable evidence to justify acceptance of this hypothesis. While the direction of change in formants was the same in the bite-block and the bite-block-plus-masking conditions, the group percent-change doubled in the latter condition. While the bite-block condition significantly lowered /i/ F2, the bite-block-plus-masking condition lowered /i/ F2 significantly more than did the bite block alone. /ae/ F2, unaffected significantly by the bite-block condition, was significantly lowered in the combined condition. It is interesting to note that /ae/ F2 variability was significantly increased in the bite-block condition (Table 7.7), suggesting that even with auditory feedback some instability was introduced. When it was removed, /ae/ F2 was significantly lowered. /I/ F1, unaffected significantly by the bite-block condition, was significantly raised in the combined condition.

Tables 7.28 and 7.29 summarized the findings for the individual adults with normal hearing in the bite-block-plus-masking condition. No significant interaction of bite-block-plus-masking was found for F2 or F2SD (Table 7.16). There was no significant interaction found for F1SD either, but four individuals exhibited a significant interaction of bite block and masking for F1 (Table 7.17). Table 7.19 displayed the post hoc tests of this interaction, collapsed across vowels, for the four individuals. For Subject N1M, the bite-block and the bite-block-plus-masking conditions were equally disruptive. They both significantly raised F1. There was no significant difference between the two conditions.

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The combined condition was more disruptive to F1 for two individuals, N4F and N5M. Neither of them exhibited significant change in the bite-block condition, but the combined condition raised F1 significantly, creating a significant difference between each condition. For N6M, there was a significant difference between the two conditions because they each resulted in significant F1 changes in opposite directions. Thus the individual profiles show a more complex picture than do the group results of the effect of pairing auditory masking with the bite-block.

Some interesting insights may be gained, however, in examining the significant interactions of bite block and masking and vowel. Table 7.20 showed that five subjects exhibited significant interactions of bite block and masking and vowel on F2. Tables 7.24 and 7.25 provide exact details, but Table 7.28 and Figures 7.21 - 7.23 provide useful summaries and overviews of the findings. It is clear that in comparing the bite-block and the bite-block-plus-masking conditions in each of the three vowels, one can find patterns where the latter condition changed formants more than, the same as, or in a different direction from the bite-block condition. In one case, for subject N6M, /ae/ F1 was less disrupted in the combined condition than in the bite-block condition. Nevertheless, two patterns emerge: the bite-block-plus-masking condition created a significantly greater lowering of F2 in /i/ in four of the five individuals who exhibited significant interactions of bite block, masking, and vowel and a significantly greater lowering of F2 in /ae/ for three of these five subjects. No such trend could be found for F1. Perhaps it is less difficult to compensate for a bite block in the tongue height dimension, when deprived of auditory feedback, than in the anteroposterior placement of the tongue, largely affecting F2. Tongue height may provide more proprioceptive feedback than place of tongue constriction. Auditory feedback may aid compensation for a bite block in that dimension. The combination of auditory deprivation and bite block does not, however, appear to be simply additive in terms of its effect. Nevertheless, the evidence is quite abundant at the group and

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at the individual level that the hypothesis that auditory feedback plays a role in compensation for a bite block must be accepted.

To be more certain of the results of the bite-block-plus-masking condition, this investigation was designed to include a masking condition, to rule out any effects of masking alone. Table 7.5 summarized the group findings for this condition. It resulted in changes in the formants in the same, neutralizing, direction seen in the bite-block condition. The percent-change figures (cf. Table 7.4 and 7.5) indicated that masking resulted in slightly larger changes than did the bite block. However, only /i/ F2 was significantly lowered in the masking condition. Table 7.6 showed that the bite-block-plus-masking condition resulted in an F2 measure that was significantly lower than those in either masking or bite-block conditions alone. Thus the combined effect is not attributable to masking alone. There were no significant findings for F1 for the group in the masking condition.

Table 7.27 summarized the masking effects for individuals. Five individuals exhibited a significant main effect of masking on F2. Two subjects, N1M and N6M, were particularly affected by masking in all three vowels. While there had been no significant findings for F1 for the group, all the subjects showed a significant main effect of masking on F1, with /i/ and /I/ most often affected. In "Chapter One" a study by Van Summers (1988) was reviewed. He examined the effects on vowel formants of 80, 90 and 100 dB SPL masking noise levels in two male adults. The results here are highly consistent with his. He found differences between his two speakers. For one man F2 was lowered and F1 was raised. The other subject showed little effect. Van Summers used isolated words spoken in citation form. It may be that a more generalized effect was seen here because producing test words in a carrier phrase may be a more challenging articulatory task.

Figures 7.21 - 7.23 visually display what post hoc tests generally showed, that the changes in the bite-block-plus-masking condition are not simply mirror images of the effects of masking alone. There were more significant findings for the combined

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condition, lending validity to an interpretation that depriving subjects of auditory feedback during vowel production with a bite block further deteriorates performance. The additional finding, that there were formant changes with masking alone, suggests that auditory feedback plays some role in on-line production, even in an adult articulatory system.

Theories of Articulatory Compensation

In "Chapter One" three accounts of articulatory compensation were reviewed. The first was a model-referenced control mechanism proposed by Lindblom, Lubker and Gay (1979) and Lubker (1979). This account places the reorganization of movement at the central nervous system level. The articulatory target is compared against centrally-received sensory information about the context. The condition of the vocal tract is "sensed". The central nervous system would sense the abnormally propped open jaw for the bite block and compare the feedback about the actual context with the intended sensory consequences. That yields an error signal that enables the central processor to predict and correct errors before incorrect movements are made. However, the findings of the formant changes in the bite-block and the bite-block-plus-masking conditions do not support the model-referenced control explanation. If the altered production posture can be sensed and compared to a central referent, the articulatory system should predict the changes needed to achieve accurate production and significant changes in formants should not have resulted in those conditions. A proponent of the account might counter with the argument that compensation was substantial and that, without perceptual tests by listeners to show that the productions were not perceived as the intended targets, the central processor made predictions and corrected errors well enough to produce a token that was a reasonable representative of the intended segment. But what of the changes to formants seen in the masking condition? If the central nervous system senses nothing abnormal about the condition of the vocal tract, why would the articulatory organization be altered?

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The coordinative structure account was also discussed in "Chapter One". It attributes articulatory compensation to the organization of musculature underlying an activity rather than to any instructions those muscles may receive from a central processor. Thus, if some members of a coordinative structure cannot vary (due to a bite block) and their states are communicated within the system, other members of the structure move in a functionally-specific manner and are constrained to act together in a cooperative fashion. In none of the conditions of this investigation were the states of the members of the coordinative structure of the tongue/jaw complex not communicated proprioceptively. Again, a proponent of the coordinative structure account might counter with the argument that compensation was substantial and that, without perceptual tests by listeners to show that the productions were not perceived as the intended targets, the members of the coordinative structure were constrained to act together well enough to produce a token that was a reasonable representative of the intended segment. But, one must ask again, what of the changes to formants seen in the masking condition? If the members of the coordinative structure communicate nothing abnormal about the condition of the vocal tract, why would the parameters of constraint be altered?

A third perspective, a theory of task dynamics or gestural theory (Saltzman and Munhall 1989), was also advanced in "Chapter One". It is an extension of the coordinative structure account in that it is built on the concept that a complex of articulators is marshaled for motion toward an articulatory goal specified as an abstract gesture. Each member of the complex can contribute to that movement. This account would suffer, too, in explaining the formant changes found in this investigation. But, perhaps, its specification of articulatory goals as abstract gestures together with Folkins and Zimmermann's (1981) proposal that while lower-level neural control systems may be important in controlling articulatory interactions, central planning may also play an important role, could account for some of the findings here. Many different processes could operate at different levels of the motor system to coordinate the articulators. That is, if abstract gestures are articulatory

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goals created with a fusion of information across sensory channels including the proprioceptive, the auditory, and the tactile, then sensing the state of the vocal tract could enable the peripheral nervous system, or the coordinative structure, to compensate in the proprioceptive domain in a highly predictive, on-line fashion, but the auditory and the tactile would only be learned as a consequence of the movement. As such, the fusion of the altered physical state with acoustic and tactile consequences would require some learning time.

Reflecting again on the findings from the adults with normal hearing, the group showed significant changes in F1 only for /I/ and only in the bite-block-plus-masking condition. Thus, "complete" compensation was made for /i/ in the F1 dimension. Perhaps the tongue/jaw complex is very skilled at adjusting tongue height to accommodate for jaw position, based on proprioceptive feedback alone. However, with /I/, a mid vowel, precise positioning may be more dependent on auditory feedback and learning whether the reorganized movement plan is adequate. F2 for /i/, on the other hand, was significantly lowered in every condition and most lowered in the combined condition. Thus the coordinated tongue/jaw structure achieved adequate tongue height for the bite block, but anteroposterior placement of the tongue suffered in every condition. Auditory feedback may be needed to augment more limited proprioceptive feedback for this maneuver on-line or to learn gradually how to fine-tune an altered production posture, as for a bite block. /ae/ F2 was also significantly lowered in the bite-block-plus-masking condition, and in the bite-block-only condition its variability was significantly increased.

The individual subjects mirrored the significant changes in F2 seen in the group. The F2 changes in either bite-block or masking conditions, and the even greater changes in the combined condition, suggest that auditory feedback plays some role in reorganization. For F1, bite-block and bite-block-plus-masking conditions resulted in frequent significant changes for /ae/, even though computer simulation predicted that the effect of a 20-mm bite block would be small. Percent changes in /ae/ F1 for several individuals far exceeded the

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predictions. It may be that while talkers can reorganize greater tongue raising when there is more jaw lowering, they may be less skilled at greater tongue lowering when there is too little jaw lowering, even with auditory feedback. In fact, as the tongue is lowered, one will reach a point at which further increases in vocal tract area can be accomplished only by lowering the jaw. In that respect, then, using a bite block to prevent opening could be more serious than using it to prevent closing.

Thus, based on the findings for the adults with normal hearing, the hypothesis that auditory feedback plays a role in compensation for a bite block is accepted.

Theoretical Question Two: To What Degree Do Children With Normal Hearing Compensate For A Bite Block And What Is The Role Of Auditory Feedback In This Compensation?

In "Chapter One", the mixed findings from studies of bite-block effects in children were reviewed. Gibson and McPhearson (1980), Edwards (1992), and Oller and MacNeilage (1983) provided acoustic evidence that young children do not compensate completely for a bite block, while Baum and Katz (1988), in a study of two groups of subjects, ages 4 to 5;6 years and 7 to 8;6 years, found that subjects produced acoustically comparable vowel tokens across both normal and bite-block conditions. This investigation sought to help resolve those discrepant findings by testing the hypothesis that four-year-old children with normal hearing perform adult-like compensation for a bite block and auditory feedback plays a role in this compensation.

Articulatory Compensation

The group results for the bite-block condition were summarized in Table 8.4 and showed that the children did not fully compensate for a 10-mm bite block. The reader will remember that computer predictions could not be made for the children in that articulatory synthesis programs have been based on the adult vocal tract. However, the findings here are very consistent with those of Edwards (1992), who used the same size and type of bite

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block and the same target words (although not in a carrier phrase). As Edwards found, F2 was lowered in each vowel. She measured F1 for /ae/ only, and found a pattern of formant lowering in the bite-block condition, just as found here. Clearly the effect of the bite block was greater for the children than for the adults, in that the percentage change was larger and that statistically significant changes were realized for F2 in every vowel and for F1 in /ae/. The adults exhibited a significant finding only for /i/ F2. These findings are also in agreement with Gibson and McPhearson (1980) and Oller and MacNeilage (1983).

It will be recalled from "Chapter One" that two studies, Smith and McLean-Muse (1987) and Baum and Katz (1988) found evidence that children compensated for a bite block. The Smith and McLean-Muse study was of articulatory movement of the jaw and the lips for labial consonants embedded in a carrier phrase. However, Edwards (1992) has pointed out that lip movements may be more ballistic in nature than those of the tongue in vowel production. This seems plausible given vowel demands for accuracy both in tongue height and place of tongue constriction. The Baum and Katz (1988) study was of groups of children and analysis was not done on an individual level. Examination of individual profiles may have led to other conclusions. For example, inspection of their table of individual child means revealed that there were six instances in which individual children in the older group of 7-8-year-olds exhibited mean formant values for specific vowels that differed more than 100 Hz between normal and bite-block conditions and twenty instances in the younger group of 4-5-year-olds.

The results for individual children in this study were summarized in Table 8.28. They mirrored the group results in that all of the children exhibited a main effect of bite block on F2 across vowels and a majority of the children exhibited a main effect of bite block on F1, with /ae/ most often affected. Table 8.31 also showed that half of the children displayed a significant main effect of bite block on F2 variability. On the individual level, there was remarkable similarity between the adults and the children with respect to direction of change and number of statistical findings of a main effect of bite block. /ae/ F1 was

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significantly changed most often in both groups. There also was evidence in both groups that there were individuals who were good compensators and others who compensated imperfectly, but the range of percent change in the children was wider for F2 (adults =.23 - 16.58%; children = .22 - 24.48%) and for F1 (adults =.38 - 24.25%; children = 1.85 - 40.43%).

While it is interesting that there are as many instances of individual statistical findings of a main effect of bite block in the adults and the children, the larger range in percent change and the group findings of a greater number of significant formant changes in the bite block condition for children support the rejection of the hypothesis that four-year-old children with normal hearing perform adult-like compensation for a bite block. Nonetheless, the children are showing individual variability with respect to this skill as early as four years of age. This evidence suggests that experience and individual skill may play a large role in the development of compensatory articulation. Coordination within muscle systems may result from late fine-tuning of articulatory skills necessary to achieve given acoustic or gestural targets.

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Table 8.6 summarized the effects of the bite-block-plus-masking condition on the group of the children. F2 was significantly lowered in every vowel and F1 in /ae/ was also significantly lowered. However, a comparison of Table 8.4 (bite-block effects) and Table 8.6 (bite-block-plus-masking effects) shows that the significance findings are nearly identical, and, in fact, the average percent change in the bite-block-plus-masking condition is less for F2 and F1 than in the bite-block condition. The suggestion that the combined condition did not result in larger effects is made even more dramatically at the individual level. Comparing Tables 8.28 (bite-block effects) and 8.30 (bite-block-plus-masking effects) reveals that all of the children showed a main effect of bite block on F2 and a majority displayed a main effect of bite block on F1, but only one child, C1F, exhibited a significant interaction of bite block and masking (See Tables 8.16 and 8.19.). The range of percent change in the bite-block-plus-masking condition is again smaller or equivalent to that in the bite-block condition (BB F2 =.22 - 24.48%; B+M F2 = .52 - 13.88%) and for F1 (BB F1 = 1.85 - 40.43%; B+M F1 = 1.9 - 45.41%).

While the group effects of the combined condition were substantial, the more restricted range of percent change in the bite-block-plus-masking condition compared to the bite-block condition, together with the failure to find significant bite-block and masking interactions in most of the individual children, suggest that the hypothesis that auditory feedback plays a role in compensation for a bite block must be rejected.

Examining the effects of the masking condition only further confirms that the removal of auditory feedback had quite a different effect on the children, compared to the adults. In the group there were no significant effects on either F2 or F1 for any vowel (See Table 8.5.). On the individual level, most of the children showed no main effect of masking on F2, but five of the six showed a main effect of masking on F1.

Taken together, there is no evidence to suggest that the effects of the bite-block-plus-masking condition could be attributed to the effects of masking alone. In fact, scanning

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Figures 8.21 - 8.23, it is apparent, at least for F2, that there is greater similarity between the bite-block and bite-block-plus-masking condition.

It is interesting to compare these findings to those of Siegel, Pick, Olsen, and Sawin (1976), who conducted a study of auditory feedback in preschool children. One of their experiments was an investigation of the effect of sidetone gain on vocal intensity. They compared vocal intensity in 3-year-old, 4-year-old, and adult participants. During speech production, the participants wore headphones and a head-mounted microphone that carried the voice signal to an audiometer. In all conditions 80dB speech-spectrum masking noise was mixed binaurally and delivered through headphones with intensity of the participant's voice set at 0dB, +10dB, and +20dB (sidetone) amplification in three conditions. The rate of decrease of vocal intensity as a function of increased sidetone gain was greater for the older subjects. They stated that their findings did "not support the supposition that auditory feedback initially is very important and then wanes in significance" (p.255).

Theories of Articulatory Compensation

In the previous discussion of theories of articulatory compensation applied to the findings in the adults with normal hearing, it was suggested that abstract gestures might be specified as a fusion of auditory, proprioceptive and tactile information. Whatever their specification, Browman and Goldstein (1990) have suggested that once abstract gestures are learned, the acoustic results of those motions are not needed to manage actively the production variability in speech. The implication is that children would be more dependent than adults on auditory information, especially in a challenging condition created by a bite block. Yet the findings here do not support that conclusion. For example, in the group, masking decreased /ae/ F2 variability, though not significantly. If young children are still in the process of fusing information across sensory channels in the development of abstract gestures, the auditory component may be less set. That is, if they are still refining movement alone, they may not have had enough experience realizing the acoustic effects of

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those movements. In that sense, the auditory information might be less informative in guiding movement. Perhaps the auditory information could even, at times, lead to more variability in an already changeable system. That may explain why depriving the children of auditory feedback in this experiment did not result in further disruption of formants, but led, in some instances, to less variability. The child may still be developing the ability to sense the state of the vocal tract to enable the peripheral nervous system, or the coordinative structure, to compensate in the proprioceptive domain in a highly predictive, on-line fashion, but has not yet learned enough of the auditory and tactile consequences of movement for that information to guide him. Thus there may be an increasing, rather than declining, use of auditory feedback over time to develop and maintain more skilled movement.

Theoretical Question Three: Are Auditory Representations Critical To The Specification Of Articulatory Reorganization For A Bite Block?

The application of this research paradigm to the adults with hearing loss made it possible to address a question that is distinct from asking about the role of auditory feedback in on-line control of articulation. This question is directed toward target specification. Is an auditory representation of a vowel target critical to compensation, serving to relate, link and constrain members of a coordinative structure or articulatory gesture? Is it essential to the development of compensatory abilities? Do speakers with a hearing loss possess articulatory compensation skills?

In "Chapter One" several studies were cited (Monsen 1976; Stein 1980; Stevens et al. 1983) that have observed that speakers with a hearing loss use jaw displacement as a primary means to differentiate vowel targets and that they exhibit deficient tongue dorsum shaping and positioning. The evidence made it plausible to question whether the jaw/tongue complex is functionally linked in the same manner as in speakers with normal hearing. A study of articulatory compensation for a bite block in five adults with profound

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hearing loss by Osberger, Netsell, and Goldgar (1986) was reviewed in "Chapter One". Three of the adults had postlingual hearing loss. The investigators concluded that speakers with hearing loss were able to reorganize articulatory gestures if the onset of hearing loss was after speech motor control was fully developed. This investigation set out to provide more details about articulatory compensation in a group of adults with prelingual profound hearing loss and a group of adults with prelingual severe hearing loss, each defined carefully with respect to severity of hearing loss, onset of loss, and speech production ability. The hypotheses set forth for these groups were that adults with profound hearing loss compensate for a bite block, as seen in adults with normal hearing, with or without auditory feedback, and that adults with severe hearing loss compensate for a bite block, as seen in adults with normal hearing, and auditory feedback plays a role in that compensation.

Articulatory Compensation

Application of this investigation to speakers with prelingual hearing loss of a severe or a profound nature made it possible to examine whether there was evidence of articulatory compensation in talkers who had developed speech production skills with severely reduced (and possibly distorted) auditory feedback or in talkers who had developed speech production skills with little or no functional auditory feedback. The effects of the bite-block condition for both groups of subjects were summarized in Table 10.4 and Table 10.7. There were no statistically significant differences found between F2 and F1 in the normal and the bite-block conditions for either group. Both groups clearly compensated for the bite block. In fact, there were instances of F2 raising in the adults with profound hearing loss, rather than lowering, as predicted by computer simulation. Average percent change across all three adult groups looked quite comparable and collectively contrasted with the larger percent change values and numerous statistically significant findings of formant change in the children. With respect to variability, the adults with profound hearing loss exhibited increased variability in /i/ and /ae/ F1 standard deviation measures in

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the bite block condition, that approached statistical significance. No other group showed significant increases in F1 variability in this condition.

The summary of bite-block effects for individual subjects was provided in Tables 10.28 and 10.31. It is on the individual level that even more interesting differences emerge. Examining changes in F2 first, it is clear from Table 10.28, which shows direction of change by vowel, that the adults with severe hearing loss showed a lowered F2 for /i/ and /I/, as had the adults and the children with normal hearing, but the adults with profound hearing loss showed as many cases of raising as lowering for /i/ and a raised F2 in /I/. Thus the F2 evidence shows that the adults with severe hearing loss look very similar to the adults and the children with normal hearing, in that a majority experienced significant F2 lowering. They did not compensate completely for the bite block. The profoundly hearing-impaired, however, do not show a failure to compensate in the close vowels, but, in fact, over-compensate in a majority of cases for /I/ and half the cases for /i/. This evidence is consistent with the cinefluorographic findings of Tye, Zimmermann, and Kelso (1983) wherein three hearing-impaired speakers showed tongue contours for /i/ that were more distinct than for adults with normal hearing, increased tongue displacement with increased jaw opening for a bite block, and tongue contours for /i/ that were preserved across jaw-fixed and jaw-free conditions. It is also interesting to note in their table of perceptual results (p.111) that listeners correctly judged /i/ productions by the congenitally hearing-impaired speaker only 50% of the time if they had been spoken in a normal condition and 87.5% of the time if they had been spoken in the bite-block condition! Further insights may be gained in returning to Tables 9.16 and 10.16 where direction and significance of F2 changes, collapsed across vowels, are summarized. Across vowels, P2F, P3M, P4M, and P5F showed almost no change, a very slight raising, or significant raising of F2. Only P1M and P6M showed a significant lowering of F2 across vowels. Referring to Figure 6.1, which provided details of average hearing loss and speech intelligibility scores of each of the adults with hearing loss, it is seen that P6M had the

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second greatest average hearing loss (107dB) recorded for subjects in these two groups, but the best speech intelligibility of the adults with profound hearing loss. P1M had the single greatest average hearing loss (110dB) of all 12 subjects and the lowest speech intelligibility of all 12 subjects, yet it will be remembered from "Chapter Nine" that he was the only adult with profound hearing loss who exhibited a significant effect of masking on F2 for every vowel. This evidence suggests that these subjects may be using residual hearing in the F2 region in everyday production in a way that the others are not, such that their responses to a bite block look more like those talkers with normal hearing or severe hearing loss. It may be that the specification of vowels for the remaining four adults with profound hearing loss is one based more on proprioceptive or tactile feedback, such that reorganization for a bite block results in overshoot to preserve the articulatory gesture, as they know it. Further support of this interpretation is offered from Table 10.16, summarizing direction and significance of F2 changes collapsed across vowels, in the adults with severe hearing loss. Here it is seen that five of the subjects exhibited either almost no change (S4M; least average hearing loss of all subjects - 63 dB) or significantly lowered second formants (S1M, S2M, S5F, and S6F) in the bite-block condition. Only S3F showed a significantly raised F2. Referring again to Figure 6.1, it is seen that she had the greatest average hearing loss in the group of adults with severe hearing loss (92 dB) and the second lowest speech intelligibility score. Her response to the bite block appears more like that of the majority of the talkers with profound hearing loss.

Turning to bite block effects on F1 (also summarized in Table 10.28), only half of the adults with profound hearing loss showed a significant main effect of bite block, but a majority of the adults with severe hearing loss did so. The range of percent change in both groups (< 27% overall) points to substantial, though not perfect, compensation compared to predictions from computer simulation. The adults with profound hearing loss were the only group of individuals who exhibited as many cases of a lowered F1 as a raised F1 for /I/. Likewise, they were the only group of individuals of whom a majority showed a

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significant main effect of bite block on F1 standard deviation. These findings appear consistent with the suggestion from the literature that adults with profound hearing loss may be more dependent on jaw position to differentiate vowels. Indeed, analysis of significant bite-block-by-vowel interactions, exhibited by a majority of the group, indicated that /ae/ was the vowel most often affected.

The hypothesis that adults with profound hearing loss compensate for a bite block, as seen in adults with normal hearing, is, in part, rejected. That is, the evidence suggests that adults with a profound hearing loss compensate for a bite block, but in a manner distinct from adults with normal hearing. The hypothesis that adults with severe hearing loss compensate for a bite block, as seen in adults with normal hearing, is accepted.

The Role of Auditory Feedback in Articulatory Compensation

The effects of the bite-block-plus-masking condition on the groups of subjects with hearing loss are shown in Table 10.6 and Table 10.9. While the bite-block-only condition did not result in any significant changes in F2 or F1 for either group of hearing-impaired talkers, the bite-block-plus-masking condition clearly deteriorated performance in the adults with severe hearing loss (doubling percent change; significantly lowering F2 in /i/ and /I/ and significantly raising F1 in /i/) while leaving the adults with profound hearing loss with essentially no significant effects, as in the bite-block condition, not even altering percent change. (Compare Tables 10.4 and 10.6.)

The analysis by individuals, summarized in Table 10.30 showed that most of the adults with profound hearing loss showed no significant interaction of bite block and masking on F2, while half of the adults with severe hearing loss did so. Half of the individuals in each group showed a significant interaction of bite block and masking on F1. In none of these cases did subsequent post hoc tests reveal a pattern of further deterioration in the combined condition at the individual level.

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Comparing across subject groups and individuals, the adults with severe hearing loss were more like the adults and the children with normal hearing than were the adults with profound hearing loss in that F2 was lowered for every vowel in the adults with severe hearing loss, while the adults with profound hearing loss exhibited a pattern of raising F2 for the high vowels. The subjects with normal hearing and the adults with severe hearing loss are also alike in that they all showed significant lowering of F2 in two or more vowels in the combined condition, but the adults with profound hearing loss showed no significant effects. While there is some similarity of direction of change in F1 across the subject groups, all but the adults with profound hearing loss exhibited a significant effect of the bite-block-plus-masking condition on at least one vowel.

The differences between the adults with severe hearing loss and the adults with profound hearing loss were already evident in the report of their speech intelligibility scores in "Chapter Six". Figure 6.1 showed the general relation between hearing loss and speech intelligibility in the twelve speakers: the greater the hearing loss the lower the speech intelligibility scores. The speakers with profound hearing loss also exhibited another widely observed characteristic associated with greater hearing loss and lower intelligibility, the production of vowels within a very restricted vowel space. For example, if one contrasts Figures 7.9 of the F1-by-F2 vowel space of one subject with normal hearing, N1M (F1:200-800Hz; F2:1500-2225Hz), with Figure 10.10 of a subject with a severe hearing loss, S1M (F1:250-800Hz; F2:1250-2000Hz), and a subject with a profound hearing loss P1M (F1:200-500Hz; F2:1500-1800Hz), it is apparent that the vowel space for the profoundly hearing-impaired speaker is very restricted compared to that of either the speaker with normal hearing or the subject with severe hearing loss.

The hypothesis set forth for the adults with profound hearing loss was that they compensate for a bite block, as seen in adults with normal hearing, with or without feedback. The adults with profound hearing loss did not fail to compensate in either condition. In fact, there is evidence of over-compensation in F2 for the close vowels in

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both conditions, with no apparent deterioration in the combined condition. Thus the hypothesis is largely supported, but the pattern of compensation is distinct from that seen in adults with normal hearing. The hypothesis set forth for the adults with severe hearing loss was that they compensate for a bite block, as seen in adults with normal hearing, and that auditory feedback plays a role in this compensation. This hypothesis is accepted. There is evidence indeed that adults with severe hearing loss compensate as substantially as adults with normal hearing and that deprivation of auditory feedback deteriorates their performance, suggesting that auditory feedback is playing some role in articulatory reorganization.

A review of the effects of the masking condition on the group of adults with severe hearing loss appears to confirm the observations from the combined condition. That is, neither the bite-block nor the masking conditions resulted in significant differences in F2 or F1, yet the combined condition resulted in significant lowering of F2 in /i/ and /I/ and significant raising in /i/ F1. Clearly the effects of the combined condition did not simply mirror the effects of masking alone.

While there were no significant findings for either group of adults with hearing loss in the masking condition, there is a surprisingly similar amount of percent change across all three adult groups for F2! (See Table 10.5.) Also, the direction of change is consistent with that seen in the bite-block condition: the adults with normal hearing and with severe hearing loss lowered F2, while the adults with profound hearing loss raised F2. For F1, the percent change in F1 is smaller in the adults with profound hearing loss than in the other two groups. These findings are consistent with an interpretation that the adults with profound hearing loss use even the small amount of residual hearing available to them to guide tongue movements in the anteroposterior dimension, but that tongue height may be monitored primarily by tactile and proprioceptive means. This interpretation is given more support in the analysis of individual profiles, the findings of which are summarized in Table 10.29. A majority of the adults with profound hearing loss showed a main effect of

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masking for F2, but not for F1. Table 9.16 showed that every individual displayed a significant main effect of masking on F2 except subject P4M, who, as shown in Figure 6.1, had the most residual hearing of anyone in the profoundly hearing-impaired group, but ranked third in speech intelligibility among those talkers. P4M's audiogram may not correlate with functional use of auditory feedback in speech production.

Theories of Articulatory Compensation

In the previous discussions of theories of articulatory compensation applied to the findings in the adults and the children with normal hearing, it was suggested that abstract gestures might be specified as a fusion of auditory, proprioceptive and tactile information and that in articulatory compensation for a bite block, the tongue/jaw complex reorganizes movement to achieve these abstract gestures. The application of this research design to the adults with profound and severe hearing loss allowed the testing of whether articulatory compensation would be achieved in talkers for whom the abstract gesture could be only a fusion of proprioceptive and tactile information with either little/no auditory information or reduced/distorted auditory information. In both cases, there was evidence of compensation. The results from the group of adults with severe hearing loss looked most like those of the adults with normal hearing. The direction of change of formants was generally the same and larger effects of the bite block were seen when it was combined with masking noise. The adults with profound hearing loss also compensated for a bite block, but the direction of change suggested an over-compensation in the F2 dimension. The combined condition did not result in a deterioration in their compensation for the bite block. These findings suggest that the adults with profound hearing loss may have abstract gestures specified in proprioceptive and tactile terms, and that in reorganization for a bite block the talkers seek to preserve the gestures by over-compensating in more forward production of the close vowels. The strategy did not change in the bite-block-plus-masking condition. Neither the adults with profound hearing loss nor the adults with severe hearing

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loss were affected by the masking condition, in which they removed hearing aids and listened to an 80dB masking noise. On the individual level, however, there were some speakers with profound hearing loss whose production was altered in masking conditions, and there was one speaker with a severe hearing loss who appeared to over-compensate for a bite block in the manner seen in the adults with profound hearing loss. These kinds of exceptions reinforce the general observation by professionals in speech/language and audiological settings that the audiogram does not always indicate how auditory feedback may be used in speech production. Thus it seems reasonable to propose from this evidence that coordinative structures for speech movement may organize themselves around specifications that are a fusion of any form of feedback to which the speaker has access. However, the better speech intelligibility scores for adults with severe hearing loss, compared to those for adults with profound hearing loss, documented in "Chapter Six", show that articulatory specifications or gestures that allow fusion of even limited or distorted auditory feedback with proprioceptive and tactile sensory channels result in more skilled production in general. Further, the results from the bite-block-plus-masking condition suggest that auditory feedback did play a role in the articulatory reorganization of the adults with severe hearing loss, such that with time and practice they might, through central planning, gradually learn how to fine-tune an altered production posture. The adults with profound hearing loss, however, already showed evidence of over-compensation in the F2 dimension. Whether, over time, they could learn tongue-lowering techniques, with restricted jaw movement, to better compensate in the F1 dimension, is an unanswered question. It is interesting to note that /ae/ F1 was most often changed across all subject groups. This finding may suggest that tongue lowering for a front, open vowel, without the aid of the jaw, is an articulatory gesture that is not within most speakers' articulatory repertoire, whether they have normal hearing or a hearing loss. Conversely, all subjects showed substantial compensation in tongue height (the F1 dimension) in close vowels produced with a more open jaw.

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In conclusion, the findings of this dissertation indicate that articulatory compensation is demonstrated in speakers with congenital profound hearing loss, for whom articulatory gestures must be specified with little or no auditory information. However, the pattern of compensation is different from that of adults with normal hearing or with severe hearing loss. Talkers appear to preserve articulatory gestures in fixed-jaw conditions in a manner that reflects the forms of feedback to which they had access during speech development. Speakers are aided by the fusion of auditory information with proprioceptive and tactile sensory information from speech movements, over time, and generally achieve better overall speech intelligibility. Thus auditory feedback, when available, becomes a means to refine and maintain precise articulatory movement and, with time, assists the substantial and more immediate, but incomplete, proprioceptive on-line articulatory compensation for a bite block.

Concluding Remarks

In "Chapter One" three accounts that have offered explanations of articulatory compensation were discussed. They included the Model-Referenced Theory, the Coordinative Structure Theory, and Gestural Theory. However, it is not clear that there are discriminable, explicit predictions of each that can be made that are empirically verifiable. Certainly this dissertation did not set forth hypotheses to attempt discriminate among them. Nevertheless, the data here suggest that none of these accounts alone addresses both the immediate, substantial compensation for the bite block seen in all of the adults in this study and the role of auditory feedback implicated by the bite-block-plus-masking effects upon the production of all but the adults with profound hearing loss. However, it may be that the accounts accurately represent speech reorganization at different levels in the control mechanism.

While many formant changes from normal condition were found to be statistically significant, the practical implications of these changes were not tested. It is not certain

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which of the changes measured acoustically would affect vowel category assignment by listeners. Perceptual study of the data was beyond the scope of this dissertation, but will be done at a future date to determine if those changes result in altered vowel identification by listeners.

For the adults with normal hearing, the evidence that removing auditory feedback affects articulatory compensation was an important finding. While it is apparent that auditory feedback plays some role in reorganization, the combination of masking and the bite block did not result in a simple additive, interactive effect. More research is clearly needed to better understand the contributions of peripheral and central speech motor processes in speech reorganization.

The unexpected finding of formant change in the masking condition for the adults with normal hearing must also be noted. While a phenomenon such as the Lombard effect is widely known as a result of masking, other production changes are not. The common observation that speech production in post-lingually deafened talkers remains remarkably well preserved for long periods after onset of their hearing loss is usually offered as evidence that auditory feedback plays a reduced role in a developed, adult articulatory system. Clearly, more research is needed regarding the role of auditory feedback in on-line monitoring of both vowel and consonant production in adult talkers.

Conversely, the finding in the children that auditory feedback did not play a role in on-line monitoring or articulatory reorganization was also unexpected. The implication is that developing children behave like adults with normal hearing, but with greater residual error, because their knowledge of the acoustic/articulatory relationship is not fully formed. Thus auditory feedback may become more important later in development, when acoustic/articulatory associations are better set, so that it may be used to refine articulation. More research is required to discover the developmental course of the importance of auditory feedback to speech organization.

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Finally, the clinical importance of auditory feedback to adults with profound hearing loss was suggested by these findings. While the effects of removal of auditory feedback were not surprising for those speakers with severe hearing loss, the immediate production effects of the masking condition that were seen in some of the individuals with profound hearing loss should give encouragement to all audiologists. The clinical implication is that the articulatory system seeks out and uses even very small amounts of residual hearing to aid production. In these cases, and more generally, clinical research needs to be focused on learning how audition is used not only for speech perception, but for production, in speakers with hearing loss.

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Appendix A: Stimuli - Word Lists

The short lists below were combined four times, each time in a changed sequence, in order to make the pseudo-randomized long stimulus word lists, also below. The long lists were counterbalanced for use across individual subjects.

Short List 1	Short List 2	Short List 3	Short List 4
hat	hit	heat	heat
hat	heat	hat	hit
hat	hit	hat	heat
hit	hat	hit	hat
hit	heat	hit	hat
heat	hit	hat	hit
heat	hat	heat	hit
hit	hat	hit	hat
heat	heat	hat	heat
heat	hat	heat	hat
hit	hit	hit	hit
hat	heat	heat	heat

Long List 1	(Short Lists 1, 2, 3, 4)				Long List 2	(Short Lists 2, 3, 4, 1)			
1.	hat	hat	hat	hit	1.	hit	heat	hit	hat
2.	hit	heat	heat	hit	2.	heat	hit	hat	hat
3.	heat	heat	hit	hat	3.	heat	hat	hit	heat
4.	hit	heat	hit	hat	4.	heat	hat	hat	hit
5.	heat	hit	hat	hat	5.	hit	hat	heat	hit
6.	heat	hat	hit	heat	6.	hat	heat	hit	heat
7.	heat	hat	hat	hit	7.	heat	hit	heat	hat
8.	hit	hat	heat	hit	8.	hat	hit	hit	hat
9.	hat	heat	hit	heat	9.	heat	hat	hit	heat
10.	heat	hit	heat	hat	10.	hat	hat	hat	hit
11.	hat	hit	hit	hat	11.	hit	heat	heat	hit
12.	heat	hat	hit	heat	12.	heat	heat	hit	hat

Long List 3	(Short Lists 3, 4, 1, 2)				Long List 4	(Short Lists 4, 1, 2, 3)			
1.	heat	hat	hat	hit	1.	heat	hit	heat	hat
2.	hit	hat	heat	hit	2.	hat	hit	hit	hat
3.	hat	heat	hit	heat	3.	heat	hat	hit	heat
4.	heat	hit	heat	hat	4.	hat	hat	hat	hit
5.	hat	hit	hit	hat	5.	hit	heat	heat	hit
6.	heat	hat	hit	heat	6.	heat	heat	hit	hat
7.	hat	hat	hat	hit	7.	hit	heat	hit	hat
8.	hit	heat	heat	hit	8.	heat	hit	hat	hat
9.	heat	heat	hit	hat	9.	heat	hat	hit	heat
10.	hit	heat	hit	hat	10.	heat	hat	hat	hit
11.	heat	hit	hat	hat	11.	hit	hat	heat	hit
12.	heat	hat	hit	heat	12.	hat	heat	hit	heat

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Appendix B: Procedures - Condition Order

Orders of condition and word lists were constructed to obtain a unique combination of each for every subject in every group.

Possible Orders of Condition	Possible Orders of Word Lists
NMBX[1]	1234
NMXB	1243
NBMX	1324
NBXM	1342
NXBM	1423
NXMB	1432
MNBX	2134
MNXB	2143
MBNX	2314
MBXN	2341
MXNB	2413
MXBN	2431
BNMX	3124
BNXM	3142
BMNX	3214
BMXN	3241
BXNM	3412
BXMN	3421
XNMB	4123
XNBM	4132
XMNB	4213
XMBN	4231
XBNM	4312
XBMN	4321

[1] N = Normal
M = Masking
B = Bite-Block
X = Bite-Block-Plus-Masking

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Appendix C1a: Three-Way Analysis of Variance: F2 for Subject N1M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	16,155.70	1	16,155.70	11.51	.0009★★
Error	227,299.90	162	1,403.09		
Masking	279,943.30	1	279,943.30	199.52	.0000★★
Error	227,299.90	162	1,403.09		
Vowel	14,000,000.00	2	6,949,464.00	4,952.98	.0000★★
Error	227,299.90	162	1,403.09		
BB, M	4,534.48	1	4,534.48	3.23	.0741
Error	227,299.90	162	1,403.09		
BB, V	26,024.20	2	13,012.10	9.27	.0002★★
Error	227,299.90	162	1,403.09		
M, V	32,354.45	2	16,177.22	11.53	.0000★★
Error	227,299.90	162	1,403.09		
BB, M, V	11,592.64	2	5,796.32	4.13	.0178★
Error	227,299.90	162	1,403.09		

Appendix C1b: Three-Way Analysis of Variance: F1 for Subject N1M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	94,945.76	1	94,945.76	97.75	.0000★★
Error	157,346.10	162	971.27		
Masking	8,538.57	1	8,538.57	8.79	.0035★★
Error	157,346.10	162	971.27		
Vowel	4,572,846.00	2	2,286,423.00	2,354.05	.0000★★
Error	157,346.10	162	971.27		
BB, M	6,758.82	1	6,758.82	6.96	.0092★★
Error	157,346.10	162	971.27		
BB, V	74,670.95	2	37,335.48	38.44	.0000★★
Error	157,346.10	162	971.27		
M, V	464.00	2	232.00	0.24	.7878
Error	157,346.10	162	971.27		
BB, M, V	14,265.96	2	7,132.98	7.34	.0009★★
Error	157,346.10	162	971.27		

★★ = $p<.01$, ★ = $p<.05$

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Appendix C1c: Three Two-Way Analyses of Variance: Standard Deviation of F2 for Subject N1M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	53.55	1	53.55	0.35	.5684
Error	1,211.05	8	151.38		
Masking	227.51	1	227.51	1.50	.2551
Error	1,211.05	8	151.38		
BB, M	185.10	1	185.10	1.22	.3010
Error	1,211.05	8	151.38		
Bite Block	53.55	1	53.55	.35	.5742
Error	910.81	6	151.80		
Vowel	459.54	2	229.77	1.51	.2936
Error	910.81	6	151.80		
BB, V	253.31	2	126.65	.83	.4790
Error	910.81	6	151.80		
Masking	227.51	1	227.51	2.04	.2032
Error	669.26	6	111.54		
Vowel	459.54	2	229.77	2.06	.2084
Error	669.26	6	111.54		
M, V	320.90	2	160.45	1.44	.3088
Error	669.26	6	111.54		

★★ = $p<.01$, ★ = $p<.05$

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Appendix C1d: Three Two-Way Analyses of Variance: Standard Deviation of F1 for Subject N1M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	261.80	1	261.80	.51	.4944
Error	4,085.62	8	510.70		
Masking	209.25	1	209.25	.41	.5400
Error	4,085.62	8	510.70		
BB, M	1.93	1	1.93	.004	.9525
Error	4,085.62	8	510.70		
Bite Block	261.80	1	261.80	1.39	.2829
Error	1,129.47	6	188.24		
Vowel	2,936.02	2	1,468.01	7.80	.0214★
Error	1,129.47	6	188.24		
BB, V	231.32	2	115.66	.61	.5718
Error	1,129.47	6	188.24		
Masking	209.25	1	209.25	2.48	.1665
Error	506.68	6	84.45		
Vowel	2,936.02	2	1,468.01	17.38	.0032★★
Error	506.68	6	84.45		
M, V	906.66	2	453.33	5.37	.0461★
Error	506.68	6	84.45		

★★ = $p<.01$, ★ = $p<.05$

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Appendix C2a: Three-Way Analysis of Variance: F2 for Subject N2F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	158,601.70	1	158,601.70	32.13	.0000★★
Error	542,940.90	110	4,935.83		
Masking	140,946.70	1	140,946.70	28.56	.0000★★
Error	542,940.90	110	4,935.83		
Vowel	20,000,000.00	1	20,000,000.00	4,136.60	.0000★★
Error	542,940.90	110	4,935.83		
BB, M	9,726.13	1	9,726.13	1.97	.1632
Error	542,940.90	110	4,935.83		
BB, V	32,939.45	1	32,939.45	6.67	.0111★
Error	542,940.90	110	4,935.83		
M, V	2,131.68	1	2,131.68	.43	.5124
Error	542,940.90	110	4,935.83		
BB, M, V	66,564.84	1	66,564.84	13.49	.0004★★
Error	542,940.90	110	4,935.83		

Appendix C2b: Three-Way Analysis of Variance: F1 for Subject N2F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	131,668.50	1	131,668.50	87.70	.0000★★
Error	165,145.20	110	1,501.32		
Masking	9,715.76	1	9,715.76	6.47	.0124★
Error	165,145.20	110	1,501.32		
Vowel	6,663,693.00	1	6,663,693.00	4,418.57	.0000★★
Error	165,145.20	110	1,501.32		
BB, M	2,623.28	1	2,623.28	1.75	.1890
Error	165,145.20	110	1,501.32		
BB, V	279,375.40	1	279,375.40	186.09	.0000★★
Error	165,145.20	110	1,501.32		
M, V	8,243.03	1	8,243.03	5.49	.0209★
Error	165,145.20	110	1,501.32		
BB, M, V	8,495.72	1	8,495.72	5.66	.0191★
Error	165,145.20	110	1,501.32		

★★ = $p<.01$, ★ = $p<.05$

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Appendix C2c: Three Two-Way Analyses of Variance: Standard Deviation of F2 for Subject N2F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	955.94	1	955.94	2.18	.2137
Error	1,752.27	4	438.07		
Masking	124.74	1	124.74	.28	.6219
Error	1,752.27	4	438.07		
BB, M	149.56	1	149.56	.34	.5904
Error	1,752.27	4	438.07		
Bite Block	955.94	1	955.94	2.37	.1983
Error	1,611.73	4	402.93		
Vowel	7.43	1	7.43	.02	.8985
Error	1,611.73	4	402.93		
BB, V	407.41	1	407.41	1.01	.3715
Error	1,611.73	4	402.93		
Masking	124.74	1	124.74	.25	.6423
Error	1,982.77	4	495.69		
Vowel	7.43	1	7.43	.01	.9085
Error	1,982.77	4	495.69		
M, V	867.57	1	867.57	1.75	.2564
Error	1,982.77	4	495.69		

★★ = $p<.01$, ★ = $p<.05$

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Appendix C2d: Three Two-Way Analyses of Variance: Standard Deviation of F1 for Subject N2F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	145.01	1	145.01	.42	.5513
Error	1,373.97	4	343.49		
Masking	1.02	1	1.02	.003	.9591
Error	1,373.97	4	343.49		
BB, M	20.22	1	20.22	.06	.8202
Error	1,373.97	4	343.49		
Bite Block	145.01	1	145.01	4.09	.1131
Error	141.77	4	35.44		
Vowel	741.13	1	741.13	20.91	.0102★
Error	141.77	4	35.44		
BB, V	512.32	1	512.32	14.45	.0191★
Error	141.77	4	35.44		
Masking	1.02	1	1.02	.01	.9463
Error	796.44	4	199.11		
Vowel	741.13	1	741.13	3.72	.1259
Error	796.44	4	199.11		
M, V	1.64	1	1.64	.01	.9321
Error	796.44	4	199.11		

★★ = $p<.01$, ★ = $p<.05$

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Appendix C3a: Three-Way Analysis of Variance: F2 for Subject N3M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	46,389.41	1	46,389.41	21.42	.0000★★
Error	392,009.90	181	2,165.80		
Masking	180,339.70	1	180,339.70	83.27	.0000★★
Error	392,009.90	181	2,165.80		
Vowel	13,000,000.00	2	6,384,228.00	2,947.75	.0000★★
Error	392,009.90	181	2,165.80		
BB, M	3,500.53	1	3,500.53	1.62	.2052
Error	392,009.90	181	2,165.80		
BB, V	11,153.39	2	5,576.70	2.57	.0790
Error	392,009.90	181	2,165.80		
M, V	1,200.56	2	600.28	.28	.7583
Error	392,009.90	181	2,165.80		
BB, M, V	41,395.39	2	20,697.70	9.56	.0001★★
Error	392,009.90	181	2,165.80		

Appendix C3b: Three-Way Analysis of Variance: F1 for Subject N3M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	8,612.22	1	8,612.22	6.41	.0122★
Error	243,312.50	181	1,344.27		
Masking	19,862.63	1	19,862.63	14.78	.0002★★
Error	243,312.50	181	1,344.27		
Vowel	10,000,000.00	2	5,134,253.00	3,819.37	.0000★★
Error	243,312.50	181	1,344.27		
BB, M	2,398.51	1	2,398.51	1.78	.1833
Error	243,312.50	181	1,344.27		
BB, V	79,782.23	2	39,891.12	29.67	.0000★★
Error	243,312.50	181	1,344.27		
M, V	16,333.83	2	8,166.92	6.08	.0028★★
Error	243,312.50	181	1,344.27		
BB, M, V	3,506.15	2	1,753.07	1.30	.2740
Error	243,312.50	181	1,344.27		

★★ = $p<.01$,★ = $p<.05$

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Appendix C3c: Three Two-Way Analyses of Variance: Standard Deviation of F2 for Subject N3M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	131.87	1	131.87	.60	.4626
Error	1,772.85	8	221.61		
Masking	19.61	1	19.61	.09	.7737
Error	1,772.85	8	221.61		
BB, M	214.21	1	214.21	.97	.3543
Error	1,772.85	8	221.61		
Bite Block	131.87	1	131.87	.84	.3959
Error	946.87	6	157.81		
Vowel	575.66	2	287.83	1.82	.2405
Error	946.87	6	157.81		
BB, V	484.14	2	242.07	1.53	.2897
Error	946.87	6	157.81		
Masking	19.61	1	19.61	.09	.7701
Error	1,258.17	6	209.69		
Vowel	575.66	2	287.83	1.37	.3230
Error	1,258.17	6	209.69		
M, V	285.10	2	142.55	.68	.5419
Error	1,258.17	6	209.69		

★★ = $p<.01$,★ = $p<.05$

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Appendix C3d: Three Two-Way Analyses of Variance: Standard Deviation of F1 for Subject N3M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	31.69	1	31.69	.15	.7083
Error	1,685.70	8	210.71		
Masking	99.07	1	99.07	.47	.5123
Error	1,685.70	8	210.71		
BB, M	13.53	1	13.53	.06	.8064
Error	1,685.70	8	210.71		
Bite Block	31.69	1	31.69	1.32	.2945
Error	144.17	6	24.03		
Vowel	1,523.66	2	761.83	31.71	.0006★★
Error	144.17	6	24.03		
BB, V	130.47	2	65.24	2.72	.1446
Error	144.17	6	24.03		
Masking	99.07	1	99.07	3.27	.1204
Error	181.60	6	30.27		
Vowel	1523.66	2	761.83	25.17	.0012★★
Error	181.60	6	30.27		
M, V	25.66	2	12.83	.42	.6727
Error	181.60	6	30.27		

★★ = $p<.01$, ★ = $p<.05$

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Appendix C4a: Three-Way Analysis of Variance: F2 for Subject N4F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	152,750.30	1	152,750.30	25.81	.0000★★
Error	1,053,358.00	178	5,917.74		
Masking	28,787.01	1	28,787.01	4.86	.0287★
Error	1,053,358.00	178	5,917.74		
Vowel	29,000,000.00	2	15,000,000.00	2,478.83	.0000★★
Error	1,053,358.00	178	5,917.74		
BB, M	3,871.03	1	3,871.03	.65	.4197
Error	1,053,358.00	178	5,917.74		
BB, V	68,238.98	2	34,119.49	5.77	.0037★★
Error	1,053,358.00	178	5,917.74		
M, V	77,905.67	2	38,952.84	6.58	.0017★★
Error	1,053,358.00	178	5,917.74		
BB, M, V	93,898.35	2	46,949.18	7.93	.0005★★
Error	1,053,358.00	178	5,917.74		

Appendix C4b: Three-Way Analysis of Variance: F1 for Subject N4F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	413.76	1	413.76	.10	.7477
Error	709,740.70	178	3,987.31		
Masking	432,509.20	1	432,509.20	108.47	.0000★★
Error	709,740.70	178	3,987.31		
Vowel	10,000,000.00	2	5,229,816.00	1,311.62	.0000★★
Error	709,740.70	178	3,987.31		
BB, M	16,092.74	1	16,092.74	4.04	.0461★
Error	709,740.70	178	3,987.31		
BB, V	74,170.61	2	37,085.30	9.30	.0001★★
Error	709,740.70	178	3,987.31		
M, V	242,119.50	2	121,059.70	30.36	.0000★★
Error	709,740.70	178	3,987.31		
BB, M, V	138,699.80	2	69,349.91	17.39	.0000★★
Error	709,740.70	178	3,987.31		

★★ = $p<.01$, ★ = $p<.05$

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Appendix C4c: Three Two-Way Analyses of Variance: Standard Deviation of F2 for Subject N4F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	634.23	1	634.23	.75	.4126
Error	6,793.82	8	849.23		
Masking	635.11	1	635.11	.75	.4123
Error	6,793.82	8	849.23		
BB, M	2,520.68	1	2,520.68	2.97	.1232
Error	6,793.82	8	849.23		
Bite Block	634.23	1	634.23	.54	.4906
Error	7,060.88	6	1,176.81		
Vowel	750.79	2	375.39	.32	.7385
Error	7,060.88	6	1,176.81		
BB, V	2,137.94	2	1,068.97	.91	.4523
Error	7,060.88	6	1,176.81		
Masking	635.11	1	635.11	.42	.5422
Error	9,133.23	6	1,522.21		
Vowel	750.79	2	375.39	.25	.7890
Error	9,133.23	6	1,522.21		
M, V	64.72	2	32.36	.02	.9790
Error	9,133.23	6	1,522.21		

★★ = $p<.01$, ★ = $p<.05$

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Appendix C4d: Three Two-Way Analyses of Variance: Standard Deviation of F1 for Subject N4F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	289.00	1	289.00	.21	.6592
Error	11,026.93	8	1,378.37		
Masking	203.28	1	203.28	.15	.7110
Error	11,026.93	8	1,378.37		
BB, M	20.62	1	20.62	.01	.9057
Error	11,026.93	8	1,378.37		
Bite Block	289.00	1	289.00	2.10	.1977
Error	826.66	6	137.78		
Vowel	9,579.90	2	4,789.95	34.77	.0005★★
Error	826.66	6	137.78		
BB, V	844.27	2	422.14	3.06	.1211
Error	826.66	6	137.78		
Masking	203.28	1	203.28	.82	.3990
Error	1,480.39	6	246.73		
Vowel	9,579.90	2	4,789.95	19.41	.0024★★
Error	1,480.39	6	246.73		
M, V	276.26	2	138.13	.56	.5985
Error	1,480.39	6	246.73		

★★ = $p<.01$, ★ = $p<.05$

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Appendix C5a: Three-Way Analysis of Variance: F2 for Subject N5M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	39,110.10	1	39,110.10	15.43	.0001★★
Error	301,635.40	119	2,534.75		
Masking	26.73	1	26.73	.01	.9184
Error	301,635.40	119	2,534.75		
Vowel	5,615,963.00	1	5,615,963.00	2,215.59	.0000★★
Error	301,635.40	119	2,534.75		
BB, M	287.81	1	287.81	.11	.7367
Error	301,635.40	119	2,534.75		
BB, V	23,008.64	1	23,008.64	9.08	.0032★★
Error	301,635.40	119	2,534.75		
M, V	14,997.08	1	14,997.08	5.92	.0165★
Error	301,635.40	119	2,534.75		
BB, M, V	51.17	1	51.17	.02	.8873
Error	301,635.40	119	2,534.75		

Appendix C5b: Three-Way Analysis of Variance: F1 for Subject N5M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	5,384.82	1	5,384.82	5.69	.0187★
Error	112,646.50	119	946.61		
Masking	76,992.81	1	76,992.81	81.34	.0000★★
Error	112,646.50	119	946.61		
Vowel	4,216,512.00	1	4,216,512.00	4,454.33	.0000★★
Error	112,646.50	119	946.61		
BB, M	16,252.60	1	16,252.60	17.17	.0001★★
Error	112,646.50	119	946.61		
BB, V	4,864.09	1	4,864.09	5.14	.0252★
Error	112,646.50	119	946.61		
M, V	130.27	1	130.27	.14	.7113
Error	112,646.50	119	946.61		
BB, M, V	.83	1	.83	.0008	.9765
Error	112,646.50	119	946.61		

★★ = $p<.01$, ★ = $p<.05$

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Appendix C5c: Three Two-Way Analyses of Variance: Standard Deviation of F2 for Subject N5M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	311.88	1	311.88	.70	.4507
Error	1,788.99	4	447.25		
Masking	687.65	1	687.65	1.54	.2828
Error	1,788.99	4	447.25		
BB, M	89.58	1	89.58	.20	.6777
Error	1,788.99	4	447.25		
Bite Block	311.88	1	311.88	1.43	.2972
Error	869.88	4	217.47		
Vowel	1,653.41	1	1,653.41	7.60	.0510
Error	869.88	4	217.47		
BB, V	42.92	1	42.92	.20	.6798
Error	869.88	4	217.47		
Masking	687.65	1	687.65	5.13	.0862
Error	536.24	4	134.06		
Vowel	1,653.41	1	1,653.41	12.33	.0246★
Error	536.24	4	134.06		
M, V	.79	1	.79	.01	.9426
Error	536.24	4	134.06		

★★ = p<.01, ★ = p<.05

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Appendix C5d: Three Two-Way Analyses of Variance: Standard Deviation of F1 for Subject N5M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	127.12	1	127.12	.47	.5301
Error	1,078.75	4	269.69		
Masking	16.39	1	16.39	.06	.8174
Error	1,078.75	4	269.69		
BB, M	9.53	1	9.53	.04	.8601
Error	1,078.75	4	269.69		
Bite Block	127.12	1	127.12	2.83	.1679
Error	179.76	4	44.94		
Vowel	656.13	1	656.13	14.60	.0188★
Error	179.76	4	44.94		
BB, V	268.77	1	268.77	5.98	.0708
Error	179.76	4	44.94		
Masking	16.39	1	16.39	.12	.7461
Error	544.28	4	136.07		
Vowel	656.13	1	656.13	4.82	.0931
Error	544.28	4	136.07		
M, V	14.99	1	14.99	.11	.7566
Error	544.28	4	136.07		

★★ = $p<.01$, ★ = $p<.05$

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Appendix C6a: Three-Way Analysis of Variance: F2 for Subject N6M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	1,055,874.00	1	1,055,874.00	365.45	.0000★★
Error	514,288.30	178	2,889.26		
Masking	488,384.80	1	488,384.80	169.03	.0000★★
Error	514,288.30	178	2,889.26		
Vowel	15,000,000.00	2	7,315,526.00	2,531.97	.0000★★
Error	514,288.30	178	2,889.26		
BB, M	7,332.94	1	7,332.94	2.54	.1129
Error	514,288.30	178	2,889.26		
BB, V	101,242.00	2	50,620.98	17.52	.0000★★
Error	514,288.30	178	2,889.26		
M, V	25,021.60	2	12,510.80	4.33	.0146★
Error	514,288.30	178	2,889.26		
BB, M, V	30,521.14	2	15,260.57	5.28	.0059★★
Error	514,288.30	178	2,889.26		

Appendix C6b: Three-Way Analysis of Variance: F1 for Subject N6M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	2,563.13	1	2,563.13	2.85	.0933
Error	160,246.00	178	900.26		
Masking	80,965.25	1	80,965.25	89.94	.0000★★
Error	160,246.00	178	900.26		
Vowel	5,521,617.00	2	2,760,808.00	3,066.69	.0000★★
Error	160,246.00	178	900.26		
BB, M	27,691.82	1	27,691.82	30.76	.0000★★
Error	160,246.00	178	900.26		
BB, V	29,429.37	2	14,714.69	16.34	.0000★★
Error	160,246.00	178	900.26		
M, V	22,178.59	2	11,089.29	12.32	.0000★★
Error	160,246.00	178	900.26		
BB, M, V	37,715.48	2	18,857.74	20.95	.0000★★
Error	160,246.00	178	900.26		

★★ = $p<.01$, ★ = $p<.05$

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Appendix C6c: Three Two-Way Analyses of Variance: Standard Deviation of F2 for Subject N6M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	10.83	1	10.83	.03	.8678
Error	2,934.67	8	366.83		
Masking	591.65	1	591.65	1.61	.2398
Error	2,934.67	8	366.83		
BB, M	52.75	1	52.75	.14	.7144
Error	2,934.67	8	366.83		
Bite Block	10.83	1	10.83	.04	.8558
Error	1,804.72	6	300.79		
Vowel	1,453.79	2	726.90	2.42	.1699
Error	1,804.72	6	300.79		
BB, V	320.56	2	160.28	.53	.6123
Error	1,804.72	6	300.79		
Masking	591.65	1	591.65	3.26	.1212
Error	1,089.91	6	181.65		
Vowel	1,453.79	2	726.90	4.00	.0787
Error	1,089.91	6	181.65		
M, V	454.56	2	227.28	1.25	.3514
Error	1,089.91	6	181.65		

★★ = $p<.01$, ★ = $p<.05$

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Appendix C6d: Three Two-Way Analyses of Variance: Standard Deviation of F1 for Subject N6M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	5.94	1	5.94	.03	.8711
Error	1,691.94	8	211.49		
Masking	.27	1	.27	.001	.9724
Error	1,691.94	8	211.49		
BB, M	23.46	1	23.46	.11	.7476
Error	1,691.94	8	211.49		
Bite Block	5.94	1	5.94	.08	.7886
Error	452.90	6	75.48		
Vowel	1,203.46	2	601.73	7.97	.0204★
Error	452.90	6	75.48		
BB, V	59.31	2	29.66	.39	.6913
Error	452.90	6	75.48		
Masking	.27	1	.27	.003	.9569
Error	509.98	6	85.00		
Vowel	1,203.46	2	601.73	7.08	.0264★
Error	509.98	6	85.00		
M, V	7.90	2	3.95	.05	.9500
Error	509.98	6	85.00		

★★ = $p<.01$, ★ = $p<.05$

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Appendix D1a: Three-Way Analysis of Variance: F2 for Subject C1F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	4,801,855.00	1	4,801,855.00	113.67	.0000★★
Error	3,675,295.00	87	42,244.77		
Masking	157,621.20	1	157,621.20	3.73	.0567
Error	3,675,295.00	87	42,244.77		
Vowel	5,052,244.00	1	5,052,244.00	119.59	.0000★★
Error	3,675,295.00	87	42,244.77		
BB, M	429,202.90	1	429,202.90	10.16	.0020★★
Error	3,675,295.00	87	42,244.77		
BB, V	17,146.76	1	17,146.76	.41	.5257
Error	3,675,295.00	87	42,244.77		
M, V	2,422.72	1	2,422.72	.06	.8113
Error	3,675,295.00	87	42,244.77		
BB, M, V	92,482.87	1	92,482.87	2.19	.1426
Error	3,675,295.00	87	42,244.77		

Appendix D1b: Three-Way Analysis of Variance: F1 for Subject C1F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	662,227.20	1	662,227.20	62.23	.0000★★
Error	925,828.40	87	10,641.70		
Masking	667,319.60	1	667,319.60	62.71	.0000★★
Error	925,828.40	87	10,641.70		
Vowel	4,355,914.00	1	4,355,914.00	409.32	.0000★★
Error	925,828.40	87	10,641.70		
BB, M	120,944.80	1	120,944.80	11.37	.0011★★
Error	925,828.40	87	10,641.70		
BB, V	967,266.90	1	967,266.90	90.89	.0000★★
Error	925,828.40	87	10,641.70		
M, V	2,488.02	1	2,488.02	.23	.6299
Error	925,828.40	87	10,641.70		
BB, M, V	157,643.10	1	157,643.10	14.81	.0002★★
Error	925,828.40	87	10,641.70		

★★ = $p<.01$, ★ = $p<.05$

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Appendix D1c: Three Two-Way Analyses of Variance: Standard Deviation of F2 for Subject C1F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	61,847.85	1	61,847.85	21.14	.0100★
Error	11,701.48	4	2,925.37		
Masking	16,508.17	1	16,508.17	5.64	.0764
Error	11,701.48	4	2,925.37		
BB, M	8,152.50	1	8,152.50	2.79	.1704
Error	11,701.48	4	2,925.37		
Bite Block	61,847.85	1	61,847.85	8.34	.0446★
Error	29,648.40	4	7,412.10		
Vowel	6,685.84	1	6,685.84	.90	.3960
Error	29,648.40	4	7,412.10		
BB, V	27.91	1	27.91	.004	.9540
Error	29,648.40	4	7,412.10		
Masking	16,508.17	1	16,508.17	.90	.3962
Error	73,255.19	4	18,313.80		
Vowel	6,685.84	1	6,685.84	.37	.5783
Error	73,255.19	4	18,313.80		
M, V	1,760.80	1	1,760.80	.10	.7720
Error	73,255.19	4	18,313.80		

★★ = $p<.01$, ★ = $p<.05$

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Appendix D1d: Three Two-Way Analyses of Variance: Standard Deviation of F1 for Subject C1F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	162.87	1	162.89	.30	.6113
Error	2,149.75	4	537.44		
Masking	67.96	1	67.96	.13	.7401
Error	2,149.75	4	537.44		
BB, M	204.04	1	204.04	.38	.5711
Error	2,149.75	4	537.44		
Bite Block	162.87	1	162.87	.29	.6183
Error	2,240.53	4	560.13		
Vowel	20.54	1	20.54	.04	.8575
Error	2,240.53	4	560.13		
BB, V	160.68	1	160.68	.29	.6206
Error	2,240.53	4	560.13		
Masking	67.96	1	67.96	.1474	.7205
Error	1,843.59	4	460.90		
Vowel	20.54	1	20.54	.04	.8431
Error	1,843.59	4	460.90		
M, V	652.53	1	652.53	1.42	.2999
Error	1,843.59	4	460.90		

Appendix D1e: One-Way Analysis of Variance: F2 of /i/ for Subject C1F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Condition	2,184,093.00	2	1,092,046.00	15.89	.0000★★
Error	1,717,616.00	25	68,705.00		

Appendix D1f: One-Way Analysis of Variance: F1 of /i/ for Subject C1F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Condition	1,467.60	2	733.80	.19	.8270
Error	95,826.51	25	3,833.06		

★★ = $p<.01$, ★ = $p<.05$

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Appendix D2a: Three-Way Analysis of Variance: F2 for Subject C2M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	413,056.40	1	413,056.40	27.31	.0000★★
Error	1,648,731.00	109	15,125.97		
Masking	119,551.60	1	119,551.60	7.90	.0059★★
Error	1,648,731.00	109	15,125.97		
Vowel	12,432,744.00	2	6,216,372.00	410.97	.0000★★
Error	1,648,731.00	109	15,125.97		
BB, M	15,478.12	1	15,478.12	1.02	.3140
Error	1,648,731.00	109	15,125.97		
BB, V	341,204.00	2	170,602.20	11.28	.0000★★
Error	1,648,731.00	109	15,125.97		
M, V	48,590.00	2	24,294.81	1.61	.2054
Error	1,648,731.00	109	15,125.97		
BB, M, V	99,670.00	2	49,834.97	3.29	.0408★
Error	1,648,731.00	109	15,125.97		

Appendix D2b: Three-Way Analysis of Variance: F1 for Subject C2M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	3,105.64	1	3,105.64	.54	.4635
Error	625,440.30	109	5,737.98		
Masking	884,247.40	1	884,247.40	154.10	.0000★★
Error	625,440.30	109	5,737.98		
Vowel	8,640,688.00	2	4,320,344.00	752.94	.0000★★
Error	625,440.30	109	5,737.98		
BB, M	889.01	1	889.01	.15	.6946
Error	625,440.30	109	5,737.98		
BB, V	261,798.4	2	130,899.20	22.81	.0000★★
Error	625,440.30	109	5,737.98		
M, V	105,754.20	2	52,877.11	9.22	.0002★★
Error	625,440.30	109	5,737.98		
BB, M, V	5,806.10	2	2,903.07	.5059	.6043
Error	625,440.30	109	5,737.98		

★★ = $p<.01$, ★ = $p<.05$

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Appendix D2c: Three Two-Way Analyses of Variance: Standard Deviation of F2 for Subject C2M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	8,353.24	1	8,353.24	11.14	.0103★
Error	5,999.85	8	749.98		
Masking	335.55	1	335.55	.45	.5224
Error	5,999.85	8	749.98		
BB, M	122.57	1	122.57	.16	.6966
Error	5,999.85	8	749.98		
Bite Block	8,353.24	1	8,353.24	28.34	.0018★★
Error	1,768.39	6	294.73		
Vowel	2,972.45	2	1,486.22	5.04	.0519
Error	1,768.39	6	294.73		
BB, V	1,717.14	2	858.57	2.91	.1306
Error	1,768.39	6	294.73		
Masking	335.55	1	335.55	.18	.6863
Error	11,198.84	6	1,866.47		
Vowel	2,972.45	2	1,486.22	.80	.4935
Error	11,198.84	6	1,866.47		
M, V	304.38	2	152.19	.08	.9227
Error	11,198.84	6	1,866.47		

★★ = $p<.01$, ★ = $p<.05$

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Appendix D2d: Three Two-Way Analyses of Variance: Standard Deviation of F1 for Subject C2M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	437.91	1	437.91	.34	.5767
Error	10,346.49	8	1,293.31		
Masking	241.86	1	241.86	.19	.6768
Error	10,346.49	8	1,293.31		
BB, M	45.61	1	45.61	.04	.8557
Error	10,346.49	8	1,293.31		
Bite Block	437.91	1	437.91	1.76	.2329
Error	1,493.22	6	248.87		
Vowel	8,343.21	2	4,171.61	16.76	.0035★★
Error	1,493.22	6	248.87		
BB, V	797.54	2	398.77	1.60	.2770
Error	1,493.22	6	248.87		
Masking	241.86	1	241.86	.84	.3947
Error	1,727.63	6	287.94		
Vowel	8,343.21	2	4,171.61	14.49	.0050★★
Error	1,727.63	6	287.94		
M, V	759.18	2	379.59	1.32	.3353
Error	1,727.63	6	287.94		

★★ = $p<.01$, ★ = $p<.05$

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Appendix D3a: Three-Way Analysis of Variance: F2 for Subject C3F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	758,961.20	1	758,961.20	21.93	.0000★★
Error	4,672,588.00	135	34,611.77		
Masking	49.99	1	49.99	.001	.9697
Error	4,672,588.00	135	34,611.77		
Vowel	13,865,288.00	2	6,932,644.00	200.30	.0000★★
Error	4,672,588.00	135	34,611.77		
BB, M	52,041.69	1	52,041.69	1.50	.2223
Error	4,672,588.00	135	34,611.77		
BB, V	41,904.56	2	20,952.28	.61	.5474
Error	4,672,588.00	135	34,611.77		
M, V	5,232.66	2	2,616.33	.08	.9272
Error	4,672,588.00	135	34,611.77		
BB, M, V	176,475.28	2	88,237.64	2.55	.0819
Error	4,672,588.00	135	34,611.77		

Appendix D3b: Three Way Analysis of Variance: F1 for Subject C3F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	260,775.60	1	260,775.60	13.59	.0003★★
Error	2,589,686.00	135	19,182.86		
Masking	154,247.00	1	154,247.00	8.04	.0053★★
Error	2,589,686.00	135	19,182.86		
Vowel	12,554,508.00	2	6,277,254.00	327.23	.0000★★
Error	2,589,686.00	135	19,182.86		
BB, M	7,054.62	1	7,054.62	.37	.5452
Error	2,589,686.00	135	19,182.86		
BB, V	482,356.40	2	241,178.20	12.57	.0000★★
Error	2,589,686.00	135	19,182.86		
M, V	29,025.95	2	14,512.98	.76	.4713
Error	2,589,686.00	135	19,182.86		
BB, M, V	290,683.80	2	145,341.90	7.58	.0008★★
Error	2,589,686.00	135	19,182.86		

★★ = $p<.01$, ★ = $p<.05$

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Appendix D3c: Three Two-Way Analyses of Variance: Standard Deviation of F2 for Subject C3F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	70.90	1	70.90	.007	.9350
Error	80,137.37	8	10,017.17		
Masking	7,581.65	1	7,581.65	.76	.4097
Error	80,137.37	8	10,017.17		
BB, M	833.04	1	833.04	.08	.7804
Error	80,137.37	8	10,017.17		
Bite Block	70.90	1	70.90	.03	.8727
Error	15,204.34	6	2,534.06		
Vowel	70,082.72	2	35,041.36	13.83	.0057★★
Error	15,204.34	6	2,534.06		
BB, V	3,264.99	2	1,632.49	.64	.5579
Error	15,204.34	6	2,534.06		
Masking	7,581.65	1	7,581.65	4.73	.0726
Error	9,616.09	6	1,602.68		
Vowel	70,082.72	2	35,041.36	21.86	.0018★★
Error	9,616.09	6	1,602.68		
M, V	1,342.49	2	671.24	.42	.6757
Error	9,616.09	6	1,602.68		

★★ = $p<.01$, ★ = $p<.05$

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Appendix D3d: Three Two-Way Analyses of Variance: Standard Deviation of F1 for Subject C3F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	15.39	1	15.39	.004	.9488
Error	28,019.14	8	3,502.39		
Masking	160.89	1	160.89	.05	.8357
Error	28,019.14	8	3,502.39		
BB, M	436.82	1	436.82	.12	.7331
Error	28,019.14	8	3,502.39		
Bite Block	15.39	1	15.39	.03	.8652
Error	2,942.67	6	490.45		
Vowel	24,711.78	2	12,355.89	25.19	.0012★★
Error	2,942.67	6	490.45		
BB, V	962.39	2	481.20	.98	.4279
Error	2,942.67	6	490.45		
Masking	160.89	1	160.89	.29	.6082
Error	3,302.79	6	550.46		
Vowel	24,711.78	2	12,355.89	22.45	.0016★★
Error	3,302.79	6	550.46		
M, V	456.78	2	228.39	.41	.6780
Error	3,302.79	6	550.46		

★★ = $p<.01$, ★ = $p<.05$

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Appendix D4a: Three-Way Analysis of Variance: F2 for Subject C4M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	91,156.52	1	91,156.52	4.54	.0358★
Error	1,868,750.00	93	20,094.09		
Masking	419.70	1	419.70	.0209	.8854
Error	1,868,750.00	93	20,094.09		
Vowel	7,905,996.00	1	7,905,996.00	393.45	.0000★★
Error	1,868,750.00	93	20,094.09		
BB, M	27,374.38	1	27,374.38	1.36	.2461
Error	1,868,750.00	93	20,094.09		
BB, V	65,154.48	1	65,154.48	3.24	.0750
Error	1,868,750.00	93	20,094.09		
M, V	14,298.49	1	14,298.49	.71	.4011
Error	1,868,750.00	93	20,094.09		
BB, M, V	7,667.33	1	7,667.33	.38	.5383
Error	1,868,750.00	93	20,094.09		

Appendix D4b: Three-Way Analysis of Variance: F1 for Subject C4M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	3,827.71	1	3,827.71	.75	.3899
Error	477,021.20	93	5,129.26		
Masking	669.95	1	669.95	.13	.7186
Error	477,021.20	93	5,129.26		
Vowel	289,921.90	1	289,921.90	56.52	.0000★★
Error	477,021.20	93	5,129.26		
BB, M	452.45	1	452.45	.09	.7671
Error	477,021.20	93	5,129.26		
BB, V	10,352.21	1	10,352.21	2.02	.1588
Error	477,021.20	93	5,129.26		
M, V	8,087.11	1	8,087.11	1.58	.2124
Error	477,021.20	93	5,129.26		
BB, M, V	3,670.09	1	3,670.09	.72	.3998
Error	477,021.20	93	5,129.26		

★★ = $p<.01$, ★ = $p<.05$

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Appendix D4c: Three Two-Way Analyses of Variance: Standard Deviation of F2 for Subject C4M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	28.28	1	28.28	.04	.8596
Error	3,179.64	4	794.91		
Masking	3,139.45	1	3,139.45	3.95	.1178
Error	3,179.64	4	794.91		
BB, M	1,613.21	1	1,613.21	2.03	.2274
Error	3,179.64	4	794.91		
Bite Block	28.28	1	28.28	.02	.8905
Error	5,254.63	4	1,313.66		
Vowel	1,664.16	1	1,664.16	1.27	.3233
Error	5,254.63	4	1,313.66		
BB, V	1,013.51	1	1,013.51	.77	.4293
Error	5,254.63	4	1,313.66		
Masking	3,139.45	1	3,139.45	4.08	.1135
Error	3,077.98	4	769.50		
Vowel	1,664.16	1	1,664.16	2.16	.2154
Error	3,077.98	4	769.50		
M, V	78.98	1	78.98	.1026	.7647
Error	3,077.98	4	769.50		

★★ = $p<.01$, ★ = $p<.05$

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Appendix D4d: Three Two-Way Analyses of Variance: Standard Deviation of F1 for Subject C4M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	40.95	1	40.95	1.69	.2634
Error	96.90	4	24.22		
Masking	2.54	1	2.54	.10	.7624
Error	96.90	4	24.22		
BB, M	154.26	1	154.26	6.37	.0651
Error	96.90	4	24.22		
Bite Block	40.95	1	40.95	.93	.3906
Error	177.04	4	44.26		
Vowel	59.98	1	59.98	1.36	.3091
Error	177.04	4	44.26		
BB, V	16.68	1	16.68	.38	.5725
Error	177.04	4	44.26		
Masking	2.54	1	2.54	.05	.8385
Error	214.71	4	53.68		
Vowel	59.98	1	59.98	1.12	.3501
Error	214.71	4	53.68		
M, V	17.42	1	17.42	.3246	.5993
Error	214.71	4	53.68		

Appendix D4e: One-Way Analysis of Variance: F2 of /ae/ for Subject C4M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Condition	139,331.00	2	69,665.52	4.32	.0256★
Error	371,007.10	23	16,130.74		

Appendix D4f: One-Way Analysis of Variance: F1 of /ae/ for Subject C4M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Condition	36,684.80	2	18,342.38	1.68	.2081
Error	250,851.40	23	10,906.58		

★★ = $p<.01$, ★ = $p<.05$

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Appendix D5a: Three-Way Analysis of Variance: F2 for Subject C5M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	2,196,638.00	1	2,196,638.00	61.99	.0000★★
Error	5,208,986.00	147	35,435.28		
Masking	35.64	1	35.64	.001	.9747
Error	5,208,986.00	147	35,435.28		
Vowel	18,500,162.00	2	9,250,081.00	261.04	.0000★★
Error	5,208,986.00	147	35,435.28		
BB, M	25,913.66	1	25,913.66	.73	.3939
Error	5,208,986.00	147	35,435.28		
BB, V	1,056,461.00	2	528,230.50	14.91	.0000★★
Error	5,208,986.00	147	35,435.28		
M, V	185,503.00	2	92,751.35	2.62	.0764
Error	5,208,986.00	147	35,435.28		
BB, M, V	63,600.82	2	31,800.41	.90	.4098
Error	5,208,986.00	147	35,435.28		

Appendix D5b: Three-Way Analysis of Variance: F1 for Subject C5M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	342,856.60	1	342,856.60	25.85	.0000★★
Error	1,949,431.00	147	13,261.44		
Masking	158,394.10	1	158,394.10	11.94	.0007★★
Error	1,949,431.00	147	13,261.44		
Vowel	16,141,876.00	2	8,070,938.00	608.60	.0000★★
Error	1,949,431.00	147	13,261.44		
BB, M	17,751.18	1	17,751.18	1.34	.2492
Error	1,949,431.00	147	13,261.44		
BB, V	1,370,739.40	2	685,369.70	51.68	.0000★★
Error	1,949,431.00	147	13,261.44		
M, V	116,451.62	2	58,225.81	4.39	.0141★
Error	1,949,431.00	147	13,261.44		
BB, M, V	58,228.72	2	29,114.36	2.20	.1149
Error	1,949,431.00	147	13,261.44		

★★ = $p<.01$, ★ = $p<.05$

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Appendix D5c: Three Two-Way Analyses of Variance: Standard Deviation of F2 for Subject C5M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	25,939.65	1	25,939.65	10.43	.0121★
Error	19,895.56	8	2,486.95		
Masking	928.21	1	928.21	.37	.5582
Error	19,895.56	8	2,486.95		
BB, M	8,177.81	1	8,177.81	3.29	.1073
Error	19,895.56	8	2,486.95		
Bite Block	25,939.65	1	25,939.65	7.66	.0325★
Error	20,315.84	6	3,385.97		
Vowel	8,012.03	2	4,006.02	1.18	.3689
Error	20,315.84	6	3,385.97		
BB, V	673.71	2	336.85	.10	.9068
Error	20,315.84	6	3,385.97		
Masking	928.21	1	928.21	.14	.7193
Error	39,239.76	6	6,539.96		
Vowel	8,012.03	2	4,006.02	.61	.5727
Error	39,239.76	6	6,539.96		
M, V	6,761.23	2	3,380.62	.52	.6207
Error	39,239.76	6	6,539.96		

★★ = $p<.01$, ★ = $p<.05$

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Appendix D5d: Three Two-Way Analyses of Variance: Standard Deviation of F1 for Subject C5M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	5,616.40	1	5,616.40	.99	.3486
Error	45,322.08	8	5,665.26		
Masking	4,954.63	1	4,954.63	.87	.3771
Error	45,322.08	8	5,665.26		
BB, M	4,944.96	1	4,944.96	.87	.3775
Error	45,322.08	8	5,665.26		
Bite Block	5,616.40	1	5,616.40	1.53	.2617
Error	21,962.63	6	3,660.44		
Vowel	27,220.44	2	13,610.22	3.72	.0890
Error	21,962.63	6	3,660.44		
BB, V	6,038.60	2	3,019.30	.8248	.4825
Error	21,962.63	6	3,660.44		
Masking	4,954.63	1	4,954.63	1.56	.2581
Error	19,050.79	6	3,175.13		
Vowel	27,220.44	2	13,610.22	4.29	.0698
Error	19,050.79	6	3,175.13		
M, V	9,612.21	2	4,806.11	1.51	.2936
Error	19,050.79	6	3,175.13		

★★ = $p<.01$, ★ = $p<.05$

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Appendix D6a: Three-Way Analysis of Variance: F2 for Subject C6F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	3,315,127.00	1	3,315,127.00	75.26	.0000★★
Error	6,475,065.00	147	44,048.00		
Masking	40,482.72	1	40,482.72	.92	.3393
Error	6,475,065.00	147	44,048.00		
Vowel	16,300,222.00	2	8,150,111.00	185.03	.0000★★
Error	6,475,065.00	147	44,048.00		
BB, M	6,998.27	1	6,998.27	.16	.6908
Error	6,475,065.00	147	44,048.00		
BB, V	285,509.60	2	142,754.80	3.24	.0419★
Error	6,475,065.00	147	44,048.00		
M, V	80,728.18	2	40,364.09	.92	.4022
Error	6,475,065.00	147	44,048.00		
BB, M, V	16,703.18	2	8,351.59	.19	.8275
Error	6,475,065.00	147	44,048.00		

Appendix D6b: Three-Way Analysis of Variance: F1 for Subject C6F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	117,997.50	1	117,997.50	10.55	.0014★★
Error	1,643,440.00	147	11,179.90		
Masking	92,740.37	1	92,740.37	8.30	.0046★★
Error	1,643,440.00	147	11,179.90		
Vowel	11,816,406.00	2	5,908,203.00	528.47	.0000★★
Error	1,643,440.00	147	11,179.90		
BB, M	914.61	1	914.61	.08	.7753
Error	1,643,440.00	147	11,179.90		
BB, V	449,612.20	2	224,806.10	20.11	.0000★★
Error	1,643,440.00	147	11,179.90		
M, V	243,952.00	2	121,976.00	10.91	.0000★★
Error	1,643,440.00	147	11,179.90		
BB, M, V	16,168.26	2	8,084.13	.72	.4870
Error	1,643,440.00	147	11,179.90		

★★ = $p<.01$, ★ = $p<.05$

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Appendix D6c: Three Two-Way Analyses of Variance: Standard Deviation of F2 for Subject C6F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	2,287.02	1	2,287.02	.30	.5986
Error	60,906.59	8	7,613.32		
Masking	1,799.94	1	1,799.94	.24	.6398
Error	60,906.59	8	7,613.32		
BB, M	12,129.22	1	12,129.22	1.59	.2424
Error	60,906.59	8	7,613.32		
Bite Block	2,287.02	1	2,287.02	.74	.4226
Error	18,533.38	6	3,088.90		
Vowel	47,779.49	2	23,889.75	7.73	.0218★
Error	18,533.38	6	3,088.90		
BB, V	8,522.87	2	44,261.44	1.38	.3214
Error	18,533.38	6	3,088.90		
Masking	1,799.94	1	1,799.94	.41	.5438
Error	26,100.85	6	4,350.14		
Vowel	47,779.49	2	23,889.75	5.49	.0441★
Error	26,100.85	6	4,350.14		
M, V	1,442.48	2	721.24	.17	.8510
Error	26,100.85	6	4,350.14		

★★ = $p<.01$, ★ = $p<.05$

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Appendix D6d: Three Two-Way Analyses of Variance: Standard Deviation of F1 for Subject C6F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	237.76	1	237.76	.11	.7516
Error	17,721.82	8	2,215.23		
Masking	2,980.77	1	2,980.77	1.35	.2795
Error	17,721.82	8	2,215.23		
BB, M	610.56	1	610.56	.28	.6138
Error	17,721.82	8	2,215.23		
Bite Block	237.76	1	237.76	.34	.5834
Error	4,249.58	6	708.26		
Vowel	7,744.68	2	3,872.34	5.47	.0445★
Error	4,249.58	6	708.26		
BB, V	9,318.90	2	4,659.45	6.58	.0307★
Error	4,249.58	6	708.26		
Masking	2,980.77	1	2,980.77	1.69	.2419
Error	10,612.08	6	1,768.68		
Vowel	7,744.68	2	3,872.34	2.19	.1932
Error	10,612.08	6	1,768.68		
M, V	213.39	2	106.69	.06	.9420
Error	10,612.08	6	1,768.68		

★★ = $p<.01$, ★ = $p<.05$

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Appendix E1a: Two-Way, Repeated Measures Analysis of Variance:Mean F2 for Group of Adults with Profound Hearing Loss

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Vowel	2371183.00	2	1185591.00	5.46	.0249★
Error	2170997.00	10	217100.00		
Condition	19222.90	3	6407.64	.45	.7226
Error	214704.90	15	14313.66		
Vowl, Cond	14080.00	6	2346.67	.54	.7738
Error	130444.40	30	4348.15		

Appendix E1b: Two-Way, Repeated Measures Analysis of Variance: Mean F1 for Group of Adults with Profound Hearing Loss

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Vowel	1365880.00	2	682940.10	10.36	.0037★★
Error	658993.00	10	65899.30		
Condition	1495.97	3	498.66	.32	.8121
Error	23511.81	15	1567.45		
Vowl, Cond	3954.81	6	659.14	.56	.7547
Error	35005.17	30	1166.84		

Appendix E1c: Two-Way, Repeated Measures Analysis of Variance: Mean F2SD for Group of Adults with Profound Hearing Loss

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Vowel	9591.12	2	4795.56	1.34	.3041
Error	35680.35	10	3568.03		
Condition	8485.84	3	2828.61	2.35	.1132
Error	18028.92	15	1201.93		
Vowl, Cond	7045.34	6	1174.22	.87	.5264
Error	40368.95	30	1345.63		

★★ = $p<.01$, ★ = $p<.05$

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Appendix E1d: Two-Way, Repeated Measures Analysis of Variance: Mean F1SD for Group of Adults with Profound Hearing Loss

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Vowel	4143.72	2	2071.86	1.82	.2120
Error	11393.00	10	1139.30		
Condition	4535.57	3	1511.86	5.50	.0095★★
Error	4125.14	15	275.01		
Vowl, Cond	414.11	6	69.02	.42	.8583
Error	4904.58	30	163.49		

★★ = p<.01, ★ = p<.05

Appendix E2: Summary of Results of Post Hoc Tests of the Main Effect of Condition on F1SD for Group of Adults with Profound Hearing Loss

Mean F1SD for Each Condition, Collapsed Across Vowels:			
N = 37.67	BB = 49.69	B+M = 52.67	M = 33.72
	N v. BB	p = .04615★	
	N v. B+M	p = .01605★	
	N v. M	p = .48530	
	BB v. B+M	p = .59780	
	BB v. M	p = .01124★	
	B+M v. M	p = .00374★★	

★★ = p<.01, ★ = p<.05

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Appendix E3a: Three-Way Analysis of Variance: F2 for Subject P1M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	829682.90	1	829682.90	115.01	.0000★★
Error	1074887.00	149	7214.01		
Masking	375939.70	1	375939.70	52.11	.0000★★
Error	1074887.00	149	7214.01		
Vowel	933691.30	2	466845.60	64.71	.0000★★
Error	1074887.00	149	7214.01		
BB, M	307245.90	1	307245.90	42.59	.0000★★
Error	1074887.00	149	7214.01		
BB, V	36831.64	2	18415.82	2.55	.0813
Error	1074887.00	149	7214.01		
M, V	2078.37	2	1039.19	.14	.8660
Error	1074887.00	149	7214.01		
BB, M, V	46659.66	2	23329.83	3.23	.0422
Error	1074887.00	149	7214.01		

Appendix E3b: Three-Way Analysis of Variance: F1 for Subject P1M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	3213.62	1	3213.62	2.04	.1555
Error	234901.10	149	1576.52		
Masking	13.33	1	13.33	.01	.9269
Error	234901.10	149	1576.52		
Vowel	117290.00	2	58644.98	37.20	.0000★★
Error	234901.10	149	1576.52		
BB, M	5699.88	1	5699.88	3.62	.0592
Error	234901.10	149	1576.52		
BB, V	149715.20	2	74857.58	47.48	.0000★★
Error	234901.10	149	1576.52		
M, V	18551.35	2	9275.67	5.88	.0035★★
Error	234901.10	149	1576.52		
BB, M, V	414.30	2	207.13	.13	.8770
Error	234901.10	149	1576.52		

★★ = $p<.01$, ★ = $p<.05$

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Appendix E3c: Three Two-Way Analyses of Variance: Standard Deviation of F2 for Subject P1M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	366.93	1	366.93	.72	.4198
Error	4058.42	8	507.30		
Masking	2094.67	1	2094.67	4.13	.0766
Error	4058.42	8	507.30		
BB, M	169.26	1	169.26	.33	.5794
Error	4058.42	8	507.30		
Bite Block	366.93	1	366.93	.37	.5634
Error	5889.37	6	981.56		
Vowel	124.67	2	62.33	.06	.9391
Error	5889.37	6	981.56		
BB, V	308.31	2	154.15	.16	.8581
Error	5889.37	6	981.56		
Masking	2094.67	1	2094.67	4.00	.0925
Error	3144.17	6	524.03		
Vowel	124.67	2	62.33	.12	.8899
Error	3144.17	6	524.03		
M, V	1325.77	2	662.88	1.26	.3480
Error	3144.17	6	524.03		

★★ = $p<.01$, ★ = $p<.05$

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Appendix E3d: Three Two-Way Analyses of Variance: Standard Deviation of F1 for Subject P1M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	236.09	1	236.09	2.52	.1510
Error	749.25	8	93.66		
Masking	20.21	1	20.21	.22	.6546
Error	749.25	8	93.66		
BB, M	8.42	1	8.42	.09	.7720
Error	749.25	8	93.66		
Bite Block	236.09	1	236.09	35.63	.0010★★
Error	39.75	6	6.63		
Vowel	622.43	2	311.21	46.97	.0002★★
Error	39.75	6	6.63		
BB, V	115.71	2	57.85	8.73	.0167★
Error	39.75	6	6.63		
Masking	20.21	1	20.21	.33	.5876
Error	369.59	6	61.60		
Vowel	622.43	2	311.21	5.05	.0517
Error	369.59	6	61.60		
M, V	1.74	2	.87	.0141	.9860
Error	369.59	6	61.60		

★★ = $p<.01$, ★ = $p<.05$

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Appendix E4a: Three-Way Analysis of Variance: F2 for Subject P2F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	15857.05	1	15857.05	1.21	.2737
Error	2208826.00	168	13147.77		
Masking	238646.00	1	238646.00	18.15	.0000★★
Error	2208826.00	168	13147.77		
Vowel	83155.51	2	41577.75	3.16	.0449★
Error	2208826.00	168	13147.77		
BB, M	20557.99	1	20557.99	1.56	.2129
Error	2208826.00	168	13147.77		
BB, V	11622.83	2	5811.42	.44	.6435
Error	2208826.00	168	13147.77		
M, V	33295.70	2	16647.85	1.27	.2846
Error	2208826.00	168	13147.77		
BB, M, V	44551.45	2	22275.72	1.69	.1869
Error	2208826.00	168	13147.77		

Appendix E4b: Three-Way Analysis of Variance: F1 for Subject P2F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	103922.20	1	103922.20	16.03	.0001★★
Error	1089332.00	168	6484.12		
Masking	2973.65	1	2973.65	.46	.4992
Error	1089332.00	168	6484.12		
Vowel	677629.00	2	338814.50	52.25	.0000★★
Error	1089332.00	168	6484.12		
BB, M	27732.30	1	27732.30	4.28	.0402
Error	1089332.00	168	6484.12		
BB, V	75777.34	2	37888.67	5.84	.0035★★
Error	1089332.00	168	6484.12		
M, V	8454.54	2	4227.27	.6520	.5223
Error	1089332.00	168	6484.12		
BB, M, V	1997.10	2	998.55	.15	.8574
Error	1089332.00	168	6484.12		

★★ = $p<.01$, ★ = $p<.05$

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Appendix E4c: Three Two-Way Analyses of Variance: Standard Deviation of F2 for Subject P2F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	5326.92	1	5326.92	4.91	.0575
Error	8675.52	8	1084.44		
Masking	5.06	1	5.06	.005	.9472
Error	8675.52	8	1084.44		
BB, M	2817.35	1	2817.35	2.60	.1457
Error	8675.52	8	1084.44		
Bite Block	5326.92	1	5326.92	4.86	.0697
Error	6581.58	6	1096.93		
Vowel	1687.62	2	843.81	.77	.5042
Error	6581.58	6	1096.93		
BB, V	3228.73	2	1614.37	1.47	.3020
Error	6581.58	6	1096.93		
Masking	5.06	1	5.06	.002	.9632
Error	13083.67	6	2180.61		
Vowel	1687.61	2	843.81	.39	.6949
Error	13083.67	6	2180.61		
M, V	2048.50	2	1024.25	.47	.6464
Error	13083.67	6	2180.61		

★★ = $p<.01$, ★ = $p<.05$

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Appendix E4d: Three Two-Way Analyses of Variance: Standard Deviation of F1 for Subject P2F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	4284.63	1	4284.63	12.79	.0072★★
Error	2679.75	8	334.97		
Masking	372.41	1	372.41	1.11	.3225
Error	2679.75	8	334.97		
BB, M	794.95	1	794.95	2.37	.1620
Error	2679.75	8	334.97		
Bite Block	4284.63	1	4284.63	10.92	.0163★
Error	2354.79	6	392.47		
Vowel	249.09	2	124.54	.3173	.7396
Error	2354.79	6	392.47		
BB, V	1243.23	2	621.61	1.58	.2803
Error	2354.79	6	392.47		
Masking	372.41	1	372.41	.33	.5870
Error	6787.80	6	1131.30		
Vowel	249.09	2	124.54	.11	.8975
Error	6787.80	6	1131.30		
M, V	722.45	2	361.22	.32	.7383
Error	6787.80	6	1131.30		

★★ = $p<.01$, ★ = $p<.05$

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Appendix E5a: Three-Way Analysis of Variance: F2 for Subject P3M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	326725.20	1	326725.20	41.80	.0000★★
Error	1117808.00	143	7816.84		
Masking	291231.70	1	291231.70	37.26	.0000★★
Error	1117808.00	143	7816.84		
Vowel	2218566.00	2	1109283.00	141.91	.0000★★
Error	1117808.00	143	7816.84		
BB, M	86.68	1	86.68	.01	.9163
Error	1117808.00	143	7816.84		
BB, V	125869.90	2	62934.97	8.05	.0005★★
Error	1117808.00	143	7816.84		
M, V	92929.02	2	46464.51	5.94	.0033★★
Error	1117808.00	143	7816.84		
BB, M, V	11931.70	2	5965.85	.76	.4681
Error	1117808.00	143	7816.84		

Appendix E5b: Three-Way Analysis of Variance: F1 for Subject P3M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	37485.60	1	37485.60	28.83	.0001★★
Error	185962.00	143	1300.43		
Masking	2441.32	1	2441.32	1.88	.1728
Error	185962.00	143	1300.43		
Vowel	1275670.00	2	637835.00	490.48	.0000★★
Error	185962.00	143	1300.43		
BB, M	.3	1	.28	.0002	.9882
Error	185962.00	143	1300.43		
BB, V	99972.27	2	49986.13	38.44	.0000★★
Error	185962.00	143	1300.43		
M, V	3250.24	2	1625.12	1.25	.2897
Error	185962.00	143	1300.43		
BB, M, V	19292.44	2	9646.22	7.42	.0009★★
Error	185962.00	143	1300.43		

★★ = $p<.01$, ★ = $p<.05$

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Appendix E5c: Three Two-Way Analyses of Variance: Standard Deviation of F2 for Subject P3M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	2648.35	1	2648.35	2.69	.1396
Error	7876.22	8	984.53		
Masking	535.34	1	535.34	.54	.4819
Error	7876.22	8	984.53		
BB, M	741.20	1	741.20	.75	.4108
Error	7876.22	8	984.53		
Bite Block	2648.35	1	2648.35	6.78	.0405★
Error	2344.60	6	390.77		
Vowel	502.29	2	251.14	.64	.5586
Error	2344.60	6	390.77		
BB, V	6305.87	2	3152.93	8.07	.0199★
Error	2344.60	6	390.77		
Masking	535.34	1	535.34	.32	.5934
Error	10111.38	6	1685.23		
Vowel	502.29	2	251.14	.15	.8646
Error	10111.38	6	1685.23		
M, V	652.10	2	326.05	.19	.8290
Error	10111.38	6	1685.23		

★★ = p<.01, ★ = p<.05

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Appendix E5d: Three Two-Way Analyses of Variance: Standard Deviation of F1 for Subject P3M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	332.85	1	332.85	2.02	.1928
Error	1317.01	8	164.63		
Masking	12.00	1	12.00	.07	.7940
Error	1317.01	8	164.63		
BB, M	56.07	1	56.07	.34	.5756
Error	1317.01	8	164.63		
Bite Block	332.85	1	332.85	2.11	.1970
Error	948.49	6	158.08		
Vowel	228.28	2	114.14	.72	.5236
Error	948.49	6	158.08		
BB, V	208.32	2	104.16	.66	.5512
Error	948.49	6	158.08		
Masking	12.00	1	12.00	.10	.7589
Error	697.67	6	116.28		
Vowel	228.28	2	114.14	.98	.4278
Error	697.67	6	116.28		
M, V	779.99	2	389.99	3.35	.1053
Error	697.67	6	116.28		

★★ = $p<.01$, ★ = $p<.05$

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Appendix E6a: Three-Way Analysis of Variance: F2 for Subject P4M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	48930.82	1	48930.82	9.53	.0024★★
Error	831750.00	162	5134.26		
Masking	130.49	1	130.49	.03	.8735
Error	831750.00	162	5134.26		
Vowel	4919369.00	2	2459684.00	479.07	.0000★★
Error	831750.00	162	5134.26		
BB, M	25855.10	1	25855.10	5.04	.0262★
Error	831750.00	162	5134.26		
BB, V	346846.60	2	173423.30	33.78	.0000★★
Error	831750.00	162	5134.26		
M, V	18511.95	2	9255.98	1.80	.1681
Error	831750.00	162	5134.26		
BB, M, V	46538.90	2	23269.46	4.53	.0122★
Error	831750.00	162	5134.26		

Appendix E6b: Three-Way Analysis of Variance: F1 for Subject P4M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	11099.98	1	11099.98	3.42	.0661
Error	525408.50	162	3243.26		
Masking	8588.46	1	8588.46	2.65	.1056
Error	525408.50	162	3243.26		
Vowel	8574350.00	2	4287175.00	1321.87	.0000★★
Error	525408.50	162	3243.26		
BB, M	22446.11	1	22446.11	6.92	.0093
Error	525408.50	162	3243.26		
BB, V	6119.60	2	3059.82	.94	.3914
Error	525408.50	162	3243.26		
M, V	20745.47	2	10372.74	3.20	.0434
Error	525408.50	162	3243.26		
BB, M, V	2361.57	2	1180.79	.36	.6954
Error	525408.50	162	3243.26		

★★ = $p<.01$, ★ = $p<.05$

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Appendix E6c: Three Two-Way Analyses of Variance: Standard Deviation of F2 for Subject P4M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	2425.93	1	2425.93	10.00	.0133★
Error	1940.03	8	242.50		
Masking	49.13	1	49.13	.20	.6646
Error	1940.03	8	242.50		
BB, M	168.15	1	168.15	.69	.4292
Error	1940.03	8	242.50		
Bite Block	2425.93	1	2425.93	12.76	.0118★
Error	1140.61	6	190.10		
Vowel	569.56	2	284.78	1.50	.2967
Error	1140.61	6	190.10		
BB, V	447.14	2	223.57	1.18	.3707
Error	1140.61	6	190.10		
Masking	49.13	1	49.13	.09	.7756
Error	3314.37	6	552.39		
Vowel	569.56	2	284.78	.52	.6214
Error	3314.37	6	552.39		
M, V	650.19	2	325.09	.59	.5843
Error	3314.37	6	552.39		

★★ = $p<.01$, ★ = $p<.05$

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Appendix E6d: Three Two-Way Analyses of Variance: Standard Deviation of F1 for Subject P4M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	1217.26	1	1217.26	1.56	.2470
Error	6242.61	8	780.33		
Masking	419.37	1	419.37	.54	.4844
Error	6242.61	8	780.33		
BB, M	168.30	1	168.30	.22	.6547
Error	6242.61	8	780.33		
Bite Block	1217.26	1	1217.26	10.44	.0179★
Error	699.80	6	116.63		
Vowel	5218.69	2	2609.34	22.37	.0017★★
Error	699.80	6	116.63		
BB, V	911.79	2	455.90	3.91	.0819
Error	699.80	6	116.63		
Masking	419.37	1	419.37	1.05	.3455
Error	2401.47	6	400.25		
Vowel	5218.69	2	2609.34	6.52	.0313★
Error	2401.47	6	400.25		
M, V	8.01	2	4.01	.01	.9901
Error	2401.47	6	400.25		

★★ = $p<.01$, ★ = $p<.05$

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Appendix E7a: Three-Way Analysis of Variance: F2 for Subject P5F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	12188.62	1	12188.62	.94	.3330
Error	1782301.00	138	12915.22		
Masking	111699.30	1	111699.30	8.65	.0038★★
Error	1782301.00	138	12915.22		
Vowel	16528488.00	2	8264244.00	639.88	.0000★★
Error	1782301.00	138	12915.22		
BB, M	13330.45	1	13330.45	1.03	.3114
Error	1782301.00	138	12915.22		
BB, V	203543.50	2	101771.70	7.88	.0006★★
Error	1782301.00	138	12915.22		
M, V	34129.98	2	17064.99	1.32	.2701
Error	1782301.00	138	12915.22		
BB, M, V	29896.80	2	14948.40	1.16	.3173
Error	1782301.00	138	12915.22		

Appendix E7b: Three-Way Analysis of Variance: F1 for Subject P5F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	2646.48	1	2646.48	1.04	.3085
Error	349494.20	138	2532.57		
Masking	40542.20	1	40542.20	16.01	.0001★★
Error	349494.20	138	2532.57		
Vowel	14009312.00	2	7004656.00	2765.83	.0000★★
Error	349494.20	138	2532.57		
BB, M	32049.01	1	32049.01	12.65	.0005★★
Error	349494.20	138	2532.57		
BB, V	44461.76	2	22230.88	8.78	.0003★★
Error	349494.20	138	2532.57		
M, V	5490.18	2	2745.09	1.08	.3411
Error	349494.20	138	2532.57		
BB, M, V	43549.84	2	21774.92	8.60	.0003★★
Error	349494.20	138	2532.57		

★★ = $p<.01$, ★ = $p<.05$

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Appendix E7c: Three Two-Way Analyses of Variance: Standard Deviation of F2 for Subject P5F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	125.13	1	125.13	.12	.7391
Error	8420.95	8	1052.62		
Masking	6.04	1	6.04	.01	.9415
Error	8420.95	8	1052.62		
BB, M	997.18	1	997.18	.95	.3589
Error	8420.95	8	1052.62		
Bite Block	125.13	1	125.13	.09	.7729
Error	8234.85	6	1372.48		
Vowel	642.36	2	321.18	.23	.7982
Error	8234.85	6	1372.48		
BB, V	546.95	2	273.48	.20	.8245
Error	8234.85	6	1372.48		
Masking	6.04	1	6.04	.01	.9145
Error	2890.54	6	481.76		
Vowel	642.36	2	321.18	.67	.5477
Error	2890.54	6	481.76		
M, V	6010.35	2	3005.18	6.24	.0342★
Error	2890.54	6	481.76		

★★ = p<.01, ★ = p<.05

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Appendix E7d: Three Two-Way Analyses of Variance: Standard Deviation of F1 for Subject P5F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	84.43	1	84.43	.07	.7963
Error	9479.64	8	1184.96		
Masking	245.44	1	245.44	.21	.6611
Error	9479.64	8	1184.96		
BB, M	75.35	1	75.35	.06	.8073
Error	9479.64	8	1184.96		
Bite Block	84.43	1	84.43	.73	.4268
Error	697.38	6	116.23		
Vowel	9091.43	2	4545.72	39.11	.0004★★
Error	697.38	6	116.23		
BB, V	11.62	2	5.81	.05	.9516
Error	697.38	6	116.23		
Masking	245.44	1	245.44	4.37	.0815
Error	336.72	6	56.12		
Vowel	9091.43	2	4545.72	81.00	.0000★★
Error	336.72	6	56.12		
M, V	211.27	2	105.63	1.88	.2320
Error	336.72	6	56.12		

★★ = $p<.01$, ★ = $p<.05$

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Appendix E8a: Three-Way Analysis of Variance: F2 for Subject P6M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	449337.40	1	449337.40	34.08	.0000★★
Error	2294079.00	174	13184.36		
Masking	52142.47	1	52142.47	3.95	.0483★
Error	2294079.00	174	13184.36		
Vowel	42000000.00	2	21000000.00	1579.81	.0000★★
Error	2294079.00	174	13184.36		
BB, M	17.88	1	17.88	.001	.9707
Error	2294079.00	174	13184.36		
BB, V	894043.00	2	447021.50	33.91	.0000★★
Error	2294079.00	174	13184.36		
M, V	79312.36	2	39656.18	3.01	.0520
Error	2294079.00	174	13184.36		
BB, M, V	18718.93	2	9359.47	.71	.4931
Error	2294079.00	174	13184.36		

Appendix E8b: Three-Way Analysis of Variance: F1 for Subject P6M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	42984.03	1	42984.03	50.42	.0000★★
Error	149188.70	175	852.51		
Masking	2.35	1	2.35	.003	.9582
Error	149188.70	175	852.51		
Vowel	3711104.00	2	1855552.00	2176.58	.0000★★
Error	149188.70	175	852.51		
BB, M	292.13	1	292.13	.34	.5590
Error	149188.70	175	852.51		
BB, V	17769.24	2	8884.62	10.42	.0001★★
Error	149188.70	175	852.51		
M, V	9741.81	2	4870.91	5.71	.0039★★
Error	149188.70	175	852.51		
BB, M, V	158.50	2	79.25	.09	.9113
Error	149188.70	175	852.51		

★★ = $p<.01$, ★ = $p<.05$

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Appendix E8c: Three Two-Way Analyses of Variance: Standard Deviation of F2 for Subject P6M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	100.34	1	100.34	.01	.9120
Error	61714.47	8	7714.31		
Masking	6847.83	1	6847.83	.89	.3737
Error	61714.47	8	7714.31		
BB, M	1089.85	1	1089.85	.14	.7168
Error	61714.47	8	7714.31		
Bite Block	100.34	1	100.34	.02	.8828
Error	25468.52	6	4244.75		
Vowel	41745.08	2	20872.54	4.92	.0544
Error	25468.52	6	4244.75		
BB, V	2438.55	2	1219.28	.29	.7601
Error	25468.52	6	4244.75		
Masking	6847.83	1	6847.83	4.99	.0669
Error	8233.15	6	1372.19		
Vowel	41745.08	2	20872.54	15.21	.0045★★
Error	8233.15	6	1372.19		
M, V	12926.42	2	6463.21	4.71	.0589
Error	8233.15	6	1372.19		

★★ = $p<.01$, ★ = $p<.05$

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Appendix E8d: Three Two-Way Analyses of Variance: Standard Deviation of F1 for Subject P6M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	315.29	1	315.29	6.51	.0341★
Error	387.28	8	48.41		
Masking	14.59	1	14.59	.30	.5980
Error	387.28	8	48.41		
BB, M	3.05	1	3.05	.06	.8081
Error	387.28	8	48.41		
Bite Block	315.29	1	315.29	7.14	.0369★
Error	264.91	6	44.15		
Vowel	126.95	2	63.47	1.44	.3090
Error	264.91	6	44.15		
BB, V	13.06	2	6.53	.15	.8656
Error	264.91	6	44.15		
Masking	14.59	1	14.59	.18	.6903
Error	500.07	6	83.34		
Vowel	126.95	2	63.47	.76	.5073
Error	500.07	6	83.34		
M, V	78.60	2	39.30	.47	.6453
Error	500.07	6	83.34		

★★ = $p<.01$, ★ = $p<.05$

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Appendix F1a: Three-Way Analysis of Variance: F2 for Subject S1M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	171080.30	1	171080.30	51.01	.0000★★
Error	576842.40	172	3353.74		
Masking	190447.20	1	190447.20	56.79	.0000★★
Error	576842.40	172	3353.74		
Vowel	8827400.00	2	4413700.00	1316.06	.0000★★
Error	576842.40	172	3353.74		
BB, M	1438.59	1	1438.59	.43	.5134
Error	576842.40	172	3353.74		
BB, V	208021.10	2	104010.50	31.01	.0000★★
Error	576842.40	172	3353.74		
M, V	3415.90	2	1707.97	.51	.6018
Error	576842.40	172	3353.74		
BB, M, V	37463.00	2	18731.51	5.59	.0044★★
Error	576842.40	172	3353.74		

Appendix F1b: Three-Way Analysis of Variance: F1 for Subject S1M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	32801.91	1	32801.91	17.49	.0000★★
Error	322551.50	172	1875.30		
Masking	16604.40	1	16604.40	8.85	.0033★★
Error	322551.50	172	1875.30		
Vowel	3909018.00	2	1954509.00	1042.24	.0000★★
Error	322551.50	172	1875.30		
BB, M	31995.62	1	31995.62	17.06	.0001★★
Error	322551.50	172	1875.30		
BB, V	7511.40	2	3755.69	2.00	.1381
Error	322551.50	172	1875.30		
M, V	20447.00	2	10223.51	5.45	.0051★★
Error	322551.50	172	1875.30		
BB, M, V	10001.50	2	5000.75	2.67	.0724
Error	322551.50	172	1875.30		

★★ = $p<.01$, ★ = $p<.05$

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Appendix F1c: Three Two-Way Analyses of Variance: Standard Deviation of F2 for Subject S1M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	315.09	1	315.09	2.01	.1945
Error	1257.17	8	157.15		
Masking	560.74	1	560.74	3.57	.0956
Error	1257.17	8	157.15		
BB, M	240.76	1	240.76	1.53	.2509
Error	1257.17	8	157.15		
Bite Block	315.09	1	315.09	1.21	.3137
Error	1563.72	6	260.62		
Vowel	100.19	2	50.09	.19	.8300
Error	1563.72	6	260.62		
BB, V	394.75	2	197.38	.76	.5090
Error	1563.72	6	260.62		
Masking	560.74	1	560.74	2.55	.1614
Error	1319.68	6	219.95		
Vowel	100.19	2	50.09	.23	.8029
Error	1319.68	6	219.95		
M, V	393.14	2	196.57	.89	.4574
Error	1319.68	6	219.95		

★★ = $p<.01$, ★ = $p<.05$

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Appendix F1d: Three Two-Way Analyses of Variance: Standard Deviation of F1 for Subject S1M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	341.65	1	341.65	1.12	.3217
Error	2450.01	8	306.25		
Masking	79.52	1	79.52	.26	.6241
Error	2450.01	8	306.25		
BB, M	442.99	1	442.99	1.45	.2635
Error	2450.01	8	306.25		
Bite Block	341.65	1	341.65	2.22	.1866
Error	922.52	6	153.75		
Vowel	2007.45	2	1003.72	6.53	.0312★
Error	922.52	6	153.75		
BB, V	42.54	2	21.27	.14	.8735
Error	922.52	6	153.75		
Masking	79.52	1	79.52	.53	.4944
Error	901.71	6	150.29		
Vowel	2007.45	2	1003.72	6.68	.0298★
Error	901.71	6	150.29		
M, V	325.49	2	162.74	1.08	.3967
Error	901.71	6	150.29		

★★ = $p<.01$, ★ = $p<.05$

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Appendix F2a: Three-Way Analysis of Variance: F2 for Subject S2M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	219029.50	1	219029.50	33.53	.0000★★
Error	1162709.00	178	6532.07		
Masking	331570.90	1	331570.90	50.76	.0000★★
Error	1162709.00	178	6532.07		
Vowel	9290392.00	2	4645196.00	711.14	.0000★★
Error	1162709.00	178	6532.07		
BB, M	14711.49	1	14711.49	2.25	.1352
Error	1162709.00	178	6532.07		
BB, V	187730.00	2	93865.04	14.37	.0000★★
Error	1162709.00	178	6532.07		
M, V	295811.00	2	147905.30	22.654	.0000★★
Error	1162709.00	178	6532.07		
BB, M, V	35002.00	2	17501.16	2.68	.0714
Error	1162709.00	178	6532.07		

Appendix F2b: Three-Way Analysis of Variance: F1 for Subject S2M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	53167.64	1	53167.64	29.67	.0000★★
Error	318969.50	178	1791.96		
Masking	8154.91	1	8154.91	4.55	.0343★
Error	318969.50	178	1791.96		
Vowel	1721207.00	2	860603.60	480.26	.0000★★
Error	318969.50	178	1791.96		
BB, M	3819.39	1	3819.39	2.13	.1461
Error	318969.50	178	1791.96		
BB, V	40817.00	2	20408.52	11.39	.0000★★
Error	318969.50	178	1791.96		
M, V	16621.30	2	8310.65	4.64	.0109★
Error	318969.50	178	1791.96		
BB, M, V	5649.70	2	2824.85	1.58	.2096
Error	318969.50	178	1791.96		

★★ = $p<.01$, ★ = $p<.05$

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Appendix F2c: Three Two-Way Analyses of Variance: Standard Deviation of F2 for Subject S2M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	88.35	1	88.35	.07	.7997
Error	10275.13	8	1284.39		
Masking	236.21	1	236.21	.18	.6794
Error	10275.13	8	1284.39		
BB, M	95.54	1	95.54	.07	.7920
Error	10275.13	8	1284.39		
Bite Block	88.35	1	88.35	.25	.6358
Error	2131.89	6	355.31		
Vowel	4695.46	2	2347.73	6.61	.0304★
Error	2131.89	6	355.31		
BB, V	3779.52	2	1889.76	5.32	.0469★
Error	2131.89	6	355.31		
Masking	236.21	1	236.21	.28	.6175
Error	5115.91	6	852.65		
Vowel	4695.46	2	2347.73	2.75	.1418
Error	5115.91	6	852.65		
M, V	647.63	2	323.82	.38	.6994
Error	5115.91	6	852.65		

★★ = $p<.01$, ★ = $p<.05$

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Appendix F2d: Three Two-Way Analyses of Variance: Standard Deviation of F1 for Subject S2M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	4.64	1	4.64	.02	.9048
Error	2435.32	8	304.41		
Masking	3.76	1	3.76	.01	.9142
Error	2435.32	8	304.41		
BB, M	111.75	1	111.75	.37	.5614
Error	2435.32	8	304.41		
Bite Block	4.64	1	4.64	.03	.8782
Error	1087.41	6	181.24		
Vowel	1367.64	2	683.82	3.77	.0869
Error	1087.41	6	181.24		
BB, V	95.78	2	47.89	.26	.7763
Error	1087.41	6	181.24		
Masking	3.76	1	3.76	.02	.8919
Error	1122.34	6	187.06		
Vowel	1367.64	2	683.82	3.66	.0916
Error	1122.34	6	187.06		
M, V	61.73	2	30.86	.17	.8516
Error	1122.34	6	187.06		

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Appendix F3a: Three-Way Analysis of Variance: F2 for Subject S3F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	486193.20	1	486193.20	83.29	.0000★★
Error	612896.50	105	5837.11		
Masking	680526.80	1	680526.80	116.59	.0000★★
Error	612896.50	105	5837.11		
Vowel	5907250.00	1	5907250.00	1012.02	.0000★★
Error	612896.50	105	5837.11		
BB, M	24032.62	1	24032.62	4.12	.0450★
Error	612896.50	105	5837.11		
BB, V	4142.58	1	4142.58	.7097	.4015
Error	612896.50	105	5837.11		
M, V	588704.30	1	588704.30	100.86	.0000★★
Error	612896.50	105	5837.11		
BB, M, V	69752.36	1	69752.36	11.95	.0008★★
Error	612896.50	105	5837.11		

Appendix F3b: Three-Way Analysis of Variance: F1 for Subject S3F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	124762.90	1	124762.90	34.68	.0000★★
Error	377781.20	105	3597.92		
Masking	121889.60	1	121889.60	33.88	.0000★★
Error	377781.20	105	3597.92		
Vowel	6861798.00	1	6861798.00	1907.16	.0000★★
Error	377781.20	105	3597.92		
BB, M	60301.98	1	60301.98	16.76	.0001★★
Error	377781.20	105	3597.92		
BB, V	15483.66	1	15483.66	4.30	.0405★
Error	377781.20	105	3597.92		
M, V	171246.10	1	171246.10	47.60	.0000★★
Error	377781.20	105	3597.92		
BB, M, V	1.84	1	1.84	.001	.9820
Error	377781.20	105	3597.92		

★★ = $p<.01$, ★ = $p<.05$

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Appendix F3c: Three Two-Way Analyses of Variance: Standard Deviation of F2 for Subject S3F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	131.06	1	131.06	.35	.5866
Error	1503.44	4	375.86		
Masking	223.24	1	223.24	.59	.4839
Error	1503.44	4	375.86		
BB, M	834.36	1	834.36	2.22	.2105
Error	1503.44	4	375.86		
Bite Block	131.06	1	131.06	.33	.5949
Error	1574.74	4	393.68		
Vowel	875.29	1	875.29	2.22	.2102
Error	1574.74	4	393.68		
BB, V	111.00	1	111.00	.28	.6235
Error	1574.74	4	393.68		
Masking	223.24	1	223.24	.65	.4641
Error	1365.87	4	341.47		
Vowel	875.29	1	875.29	2.56	.1846
Error	1365.87	4	341.47		
M, V	227.70	1	227.70	.67	.4600
Error	1365.87	4	341.47		

★★ = $p<.01$, ★ = $p<.05$

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Appendix F3d: Three Two-Way Analyses of Variance: Standard Deviation of F1 for Subject S3F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	106.73	1	106.73	.10	.7658
Error	4199.33	4	1049.83		
Masking	134.15	1	134.15	.13	.7388
Error	4199.33	4	1049.83		
BB, M	101.53	1	101.53	.10	.7713
Error	4199.33	4	1049.83		
Bite Block	106.73	1	106.73	.18	.6909
Error	2333.55	4	583.39		
Vowel	1438.63	1	1438.63	2.47	.1914
Error	2333.55	4	583.39		
BB, V	662.84	1	662.84	1.14	.3465
Error	2333.55	4	583.39		
Masking	134.15	1	134.15	.34	.5886
Error	1555.97	4	388.99		
Vowel	1438.63	1	1438.63	3.70	.1268
Error	1555.97	4	388.99		
M, V	1412.99	1	1412.99	3.63	.1294
Error	1555.97	4	388.99		

Appendix F3e: One-Way Analysis of Variance: F2 of /I/ for Subject S3F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Condition	82771.30	2	41385.67	2.71	.0866
Error	366024.70	24	15251.03		

Appendix F3f: One-Way Analysis of Variance: F1 of /I/ for Subject S3F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Condition	351.73	2	175.86	.18	.8383
Error	23752.79	24	989.70		

★★ = $p<.01$, ★ = $p<.05$

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Appendix F4a: Three-Way Analysis of Variance: F2 for Subject S4M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	1040.22	1	1040.22	.17	.6837
Error	704581.90	113	6235.24		
Masking	1460469.00	1	1460469.00	234.23	.0000★★
Error	704581.90	113	6235.24		
Vowel	2520439.00	1	2520439.00	404.23	.0000★★
Error	704581.90	113	6235.24		
BB, M	14191.61	1	14191.61	2.28	.1342
Error	704581.90	113	6235.24		
BB, V	558.19	1	558.19	.09	.7653
Error	704581.90	113	6235.24		
M, V	27631.44	1	27631.44	4.43	.0375★
Error	704581.90	113	6235.24		
BB, M, V	35008.93	1	35008.93	5.61	.0195★
Error	704581.90	113	6235.24		

Appendix F4b: Three-Way Analysis of Variance: F1 for Subject S4M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	1984.62	1	1984.62	1.26	.2650
Error	178677.60	113	1581.22		
Masking	8164.96	1	8164.96	5.16	.0250★
Error	178677.60	113	1581.22		
Vowel	4058213.00	1	4058213.00	2566.51	.0000★★
Error	178677.60	113	1581.22		
BB, M	2316.21	1	2316.21	1.46	.2287
Error	178677.60	113	1581.22		
BB, V	.27	1	.27	.0002	.9896
Error	178677.60	113	1581.22		
M, V	160393.80	1	160393.80	101.44	.0000★★
Error	178677.60	113	1581.22		
BB, M, V	136.55	1	136.55	.09	.7694
Error	178677.60	113	1581.22		

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Appendix F4c: Three Two-Way Analyses of Variance: Standard Deviation of F2 for Subject S4M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	284.77	1	284.77	.29	.6180
Error	3910.11	4	977.53		
Masking	437.34	1	437.34	.45	.5402
Error	3910.11	4	977.53		
BB, M	593.92	1	593.92	.61	.4792
Error	3910.11	4	977.53		
Bite Block	284.77	1	284.77	.27	.6305
Error	4212.53	4	1053.13		
Vowel	347.82	1	347.82	.33	.5963
Error	4212.53	4	1053.13		
BB, V	381.02	1	381.02	.36	.5799
Error	4212.53	4	1053.13		
Masking	437.34	1	437.34	.49	.5227
Error	3573.41	4	893.35		
Vowel	347.82	1	347.82	.39	.5665
Error	3573.41	4	893.35		
M, V	867.57	1	867.57	.97	.3802
Error	3573.41	4	893.35		

★★ = $p<.01$, ★ = $p<.05$

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Appendix F4d: Three Two-Way Analyses of Variance: Standard Deviation of F1 for Subject S4M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	.42	1	.42	.01	.9435
Error	293.92	4	73.48		
Masking	11.40	1	11.40	.1551	.7138
Error	293.92	4	73.48		
BB, M	68.15	1	68.15	.93	.3901
Error	293.92	4	73.48		
Bite Block	.42	1	.42	.01	.9183
Error	140.30	4	35.07		
Vowel	230.59	1	230.59	6.57	.0624
Error	140.30	4	35.07		
BB, V	2.59	1	2.59	.07	.7994
Error	140.30	4	35.07		
Masking	11.40	1	11.40	.64	.4694
Error	71.57	4	17.89		
Vowel	230.59	1	230.59	12.89	.0230★
Error	71.57	4	17.89		
M, V	60.34	1	60.34	3.37	.1402
Error	71.57	4	17.89		

Appendix F4e: One-Way Analysis of Variance: F2 of /i/ for Subject S4M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Condition	417331.90	2	208665.90	53.33	.0000★★
Error	109564.10	28	3913.01		

Appendix F4f: One-Way Analysis of Variance: F1 of /i/ for Subject S4M

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Condition	2382.02	2	1191.01	2.27	.1219
Error	14682.82	28	524.39		

★★ = $p<.01$, ★ = $p<.05$

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Appendix F5a: Three-Way Analysis of Variance: F2 for Subject S5F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	77391.96	1	77391.96	7.57	.0070★★
Error	1063447.00	104	10225.45		
Masking	1409.42	1	1409.42	.14	.7112
Error	1063447.00	104	10225.45		
Vowel	2167705.00	1	2167705.00	211.99	.0000★★
Error	1063447.00	104	10225.45		
BB, M	104353.60	1	104353.60	10.21	.0019★★
Error	1063447.00	104	10225.45		
BB, V	25.36	1	25.36	.002	.9604
Error	1063447.00	104	10225.45		
M, V	83774.42	1	83774.42	8.19	.0051★★
Error	1063447.00	104	10225.45		
BB, M, V	13538.48	1	13538.48	1.32	.2525
Error	1063447.00	104	10225.45		

Appendix F5b: Three-Way Analysis of Variance: F1 for Subject S5F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	60433.12	1	60433.12	15.38	.0002★★
Error	408562.50	104	3928.49		
Masking	101976.90	1	101976.90	25.96	.0000★★
Error	408562.50	104	3928.49		
Vowel	4595506.00	1	4595506.00	1169.79	.0000★★
Error	408562.50	104	3928.49		
BB, M	53989.51	1	53989.51	13.74	.0003★★
Error	408562.50	104	3928.49		
BB, V	138.93	1	138.93	.04	.8512
Error	408562.50	104	3928.49		
M, V	37934.40	1	37934.40	9.66	.0024★★
Error	408562.50	104	3928.49		
BB, M, V	41443.01	1	41443.01	10.55	.0016★★
Error	408562.50	104	3928.49		

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Appendix F5c: Three Two-Way Analyses of Variance: Standard Deviation of F2 for Subject S5F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	6112.86	1	6112.86	8.36	.0445★
Error	2924.45	4	731.11		
Masking	297.92	1	297.92	.41	.5580
Error	2924.45	4	731.11		
BB, M	2118.35	1	2118.35	2.90	.1639
Error	2924.45	4	731.11		
Bite Block	6112.86	1	6112.86	6.13	.0685
Error	3986.26	4	996.57		
Vowel	6.63	1	6.63	.01	.9389
Error	3986.26	4	996.57		
BB, V	1347.84	1	1347.84	1.35	.3095
Error	3986.26	4	996.57		
Masking	297.92	1	297.92	.12	.7467
Error	9949.52	4	2487.38		
Vowel	6.63	1	6.63	.003	.9613
Error	9949.52	4	2487.38		
M, V	1199.52	1	1199.52	.48	.5256
Error	9949.52	4	2487.38		

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Appendix F5d: Three Two-Way Analyses of Variance: Standard Deviation of F1 for Subject S5F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	3.05	1	3.05	.002	.9667
Error	6196.83	4	1549.21		
Masking	91.80	1	91.80	.06	.8196
Error	6196.83	4	1549.21		
BB, M	47.82	1	47.82	.03	.8691
Error	6196.83	4	1549.21		
Bite Block	3.05	1	3.05	.02	.8999
Error	680.45	4	170.11		
Vowel	5647.72	1	5647.72	33.20	.0045★★
Error	680.45	4	170.11		
BB, V	8.28	1	8.28	.05	.8362
Error	680.45	4	170.11		
Masking	91.80	1	91.80	2.75	.1723
Error	133.33	4	33.33		
Vowel	5647.72	1	5647.72	169.43	.0002★★
Error	133.33	4	33.33		
M, V	466.65	1	466.65	14.00	.0201★
Error	133.33	4	33.33		

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Appendix F6a: Three-Way Analysis of Variance: F2 for Subject S6F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	467215.60	1	467215.60	41.94	.0000★★
Error	1916130.00	172	11140.29		
Masking	171272.50	1	171272.50	15.37	.0001★★
Error	1916130.00	172	11140.29		
Vowel	16000000.00	2	8023009.00	720.18	.0000★★
Error	1916130.00	172	11140.29		
BB, M	55220.83	1	55220.83	4.96	.0273★
Error	1916130.00	172	11140.29		
BB, V	109794.00	2	54896.93	4.93	.0083★★
Error	1916130.00	172	11140.29		
M, V	23635.00	2	11817.40	1.06	.3484
Error	1916130.00	172	11140.29		
BB, M, V	47669.00	2	23834.44	2.14	.1208
Error	1916130.00	172	11140.29		

Appendix F6b: Three-Way Analysis of Variance: F1 for Subject S6F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	16529.06	1	16529.06	5.57	.0194★
Error	510140.70	172	2965.93		
Masking	523.58	1	523.58	.18	.6749
Error	510140.70	172	2965.93		
Vowel	8904158.00	2	4452079.00	1501.07	.0000★★
Error	510140.70	172	2965.93		
BB, M	4262.57	1	4262.57	1.44	.2322
Error	510140.70	172	2965.93		
BB, V	22514.00	2	11256.99	3.80	.0244★
Error	510140.70	172	2965.93		
M, V	11753.70	2	5876.83	1.98	.1410
Error	510140.70	172	2965.93		
BB, M, V	5392.00	2	2696.00	.91	.4049
Error	510140.70	172	2965.93		

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Appendix F6c: Three Two-Way Analyses of Variance: Standard Deviation of F2 for Subject S6F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	3090.91	1	3090.91	.66	.4412
Error	37664.66	8	4708.08		
Masking	5121.61	1	5121.61	1.09	.3274
Error	37664.66	8	4708.08		
BB, M	2414.85	1	2414.85	.51	.4943
Error	37664.66	8	4708.08		
Bite Block	3090.91	1	3090.91	.79	.4096
Error	23616.41	6	3936.07		
Vowel	11384.45	2	5692.23	1.45	.3072
Error	23616.41	6	3936.07		
BB, V	10200.27	2	5100.13	1.30	.3406
Error	23616.41	6	3936.07		
Masking	5121.61	1	5121.61	1.25	.3068
Error	24635.23	6	4105.87		
Vowel	11384.45	2	5692.23	1.39	.3199
Error	24635.23	6	4105.87		
M, V	7150.74	2	3575.37	.87	.4655
Error	24635.23	6	4105.87		

★★ = $p<.01$, ★ = $p<.05$

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Appendix F6d: Three Two-Way Analyses of Variance: Standard Deviation of F1 for Subject S6F

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Bite Block	651.36	1	651.36	1.09	.3277
Error	4795.95	8	599.49		
Masking	53.72	1	53.72	.09	.7723
Error	4795.95	8	599.49		
BB, M	5.56	1	5.56	.01	.9256
Error	4795.95	8	599.49		
Bite Block	651.36	1	651.36	1.89	.2180
Error	2064.26	6	344.04		
Vowel	112.66	2	56.33	.16	.8526
Error	2064.26	6	344.04		
BB, V	2678.32	2	1339.16	3.89	.0825
Error	2064.26	6	344.04		
Masking	53.72	1	53.72	.07	.7961
Error	4417.37	6	736.23		
Vowel	112.66	2	56.33	.08	.9272
Error	4417.37	6	736.23		
M, V	922.85	2	461.42	.63	.5660
Error	4417.37	6	736.23		

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Appendix G1a: Repeated Measures, Two-Way Analysis of Variance: Mean RMS Amplitude in dB for Adults with Profound Hearing Loss

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Vowel	278.15	2	139.08	6.49	.0156★
Error	214.14	10	21.41		
Condition	121.82	3	40.61	3.55	.0402★
Error	171.53	15	11.44		
V, C	15.52	6	2.59	1.38	.2546
Error	56.21	30	1.87		

Appendix G1b: Repeated Measures, Two-Way Analysis of Variance: dB SD for Adults with Profound Hearing Loss

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Vowel	.90	2	.45	.36	.7073
Error	12.52	10	1.25		
Condition	1.20	3	.40	.56	.6522
Error	10.78	15	.72		
V, C	2.47	6	.41	1.32	.2768
Error	9.32	30	.31		

Appendix G1c: Repeated Measures, Two-Way Analysis of Variance: Mean F0 for Adults with Profound Hearing Loss

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Vowel	15758.31	2	7879.15	5.37	.0260★
Error	14666.20	10	1466.62		
Condition	3799.85	3	1266.62	6.93	.0038★★
Error	2739.75	15	182.65		
V, C	196.03	6	32.67	.67	.6755
Error	1465.89	30	48.86		

Appendix G1d: Repeated Measures, Two-Way Analysis of Variance: F0 SD for Adults with Profound Hearing Loss

	Sum of Squares	Degrees of Freedom	Mean Square	F	Tail Probability
Vowel	44.06	2	22.03	.44	.6588
Error	506.23	10	50.62		
Condition	421.84	3	140.61	7.04	.0035 ★★
Error	299.44	15	19.96		
V, C	38.64	6	6.44	.78	.5931
Error	248.14	30	8.27		

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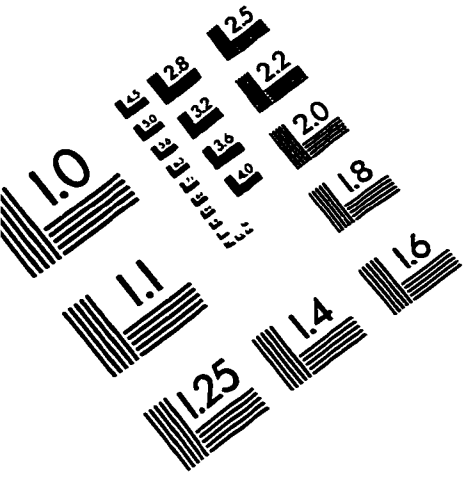
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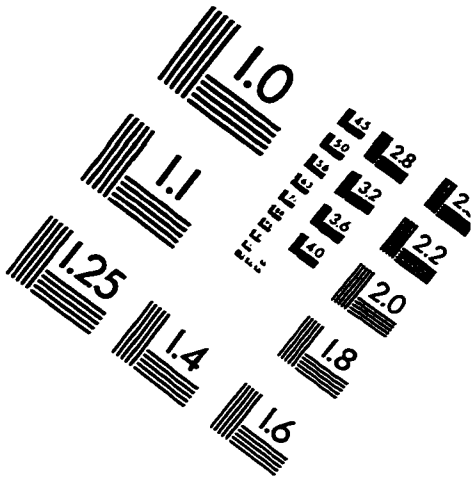
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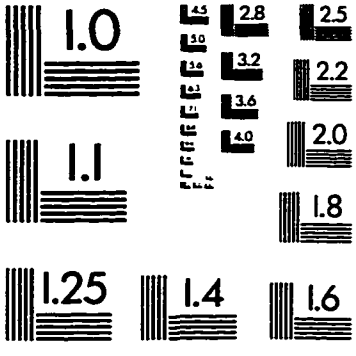
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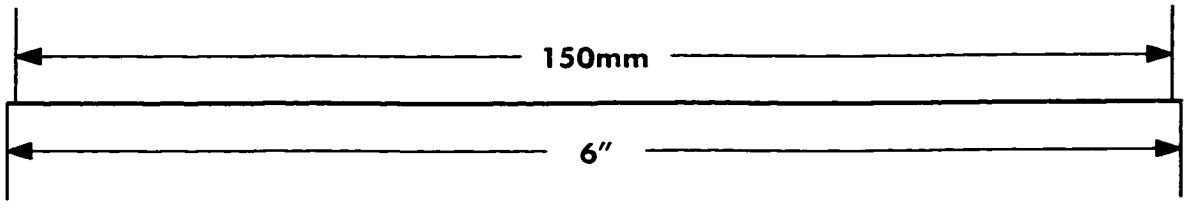
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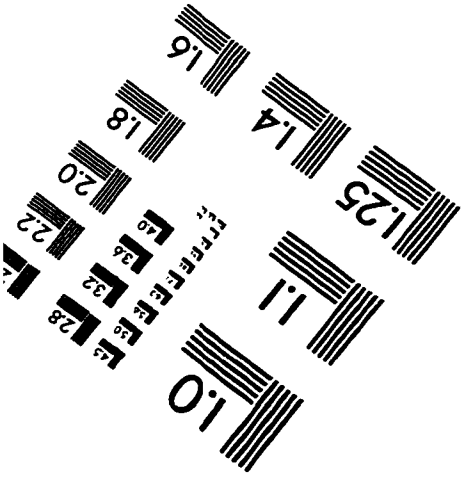
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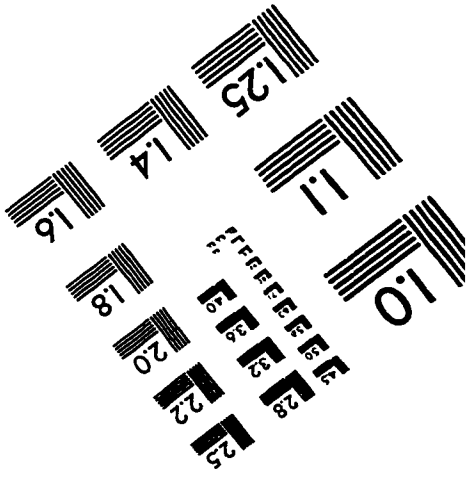












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