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**THE EFFECTS OF SPECTRALLY SHAPED NOISE MASKING ON CORTICAL
AUDITORY EVENT-RELATED POTENTIALS TO SPEECH SOUNDS**

by
Brett A. Martin

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

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This manuscript has been read and accepted for the Graduate Faculty in Speech and Hearing Sciences in satisfaction of the dissertation requirement for the degree of Doctor of Philosophy.

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ABSTRACT**THE EFFECTS OF SPECTRALLY SHAPED NOISE MASKING ON CORTICAL AUDITORY
EVENT-RELATED POTENTIALS TO SPEECH SOUNDS**

by

BRETT A. MARTIN

Advisor: David R. Stapells, Ph.D.

This dissertation examines the effects of decreased audibility produced by spectrally shaped noise masking on cortical auditory event-related potentials (ERPs) to speech sounds /ba/ and /da/. High-pass noise masking studies examined the effects of decreased audibility for high-frequency spectral regions. Results indicated that as the high-pass noise masker cutoff was lowered from 2000 to 1000 Hz, cortical ERPs MMN, N2, P3, and behavioral measures (d', RT) all showed significant changes. Amplitudes decreased and latencies increased. N1 showed a different pattern of results as a function of high-pass noise masking, with amplitudes decreasing and latencies increasing gradually as the masker cutoff was lowered. Low-pass noise masking studies examined the effects of decreased audibility for low-frequency spectral regions. Results indicated that as the low-pass noise masker was raised to from 500 to 1000-2000 Hz, ERPs MMN, N2, P3 and behavioral measures all changed significantly. N1 again showed different results, particularly for speech sounds presented at 80 dB SPL. Crossover point analyses examining the contributions of selected frequency regions to behavioral and electrophysiological responses to the speech sounds also showed a different pattern of results for N1 compared to the other measures. Based on results of the studies, N1 appears to be related to the presence of audible stimulus energy, being present when speech sounds were audible, whether or not they were discriminable. MMN, N2 and P3 appear to be related to speech sound discrimination, being present only when

behavioral results indicated audible speech sounds were discriminable. The speech sounds were discriminable only when there was spectral energy in the region of the second formant transition for /ba/ and /da/.

PREFACE

The focus of this dissertation is on the effects of spectrally shaped noise masking on cortical auditory event-related potentials (ERPs) to speech sounds /ba/ and /da/. The dissertation consists of eight chapters: (1) a review of the literature, (2) a "purpose/significance of research" chapter, (3,4,5) three research papers, (6) a fourth research paper that integrates the results of the three preceding research studies, (7) a brief summary, and (8) a references cited section. The research papers the dissertation comprises are:

- 1) The effects of decreased audibility produced by high-pass noise masking on cortical auditory event-related potentials N1, N2 and P3 to speech sounds /ba/ and /da/.
- 2) The effects of decreased audibility produced by high-pass noise masking on cortical auditory event-related potentials N1 and the mismatch negativity to speech sounds /ba/ and /da/.
- 3) The effects of decreased audibility produced by low-pass noise masking on cortical auditory event-related potentials N1, MMN, N2 and P3 to speech sounds /ba/ and /da/.
- 4) The contributions of selected frequency regions to behavioral and electrophysiological responses to /ba/ and /da/.

Each paper is intended as a stand-alone research paper. There is necessarily some overlap between papers. To minimize some of this repetition, references are listed at the end of the dissertation.

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Chapter 1:
REVIEW OF THE LITERATURE

1A. Overview of Cortical Auditory Event-Related Potentials

Event-related potentials (ERPs) are changes in the ongoing electroencephalogram (EEG) that are time-locked to sensory, motor, or cognitive events. They provide a means of measuring the timing and sequence of information processing, such as speech sound processing (e.g., Hillyard and Picton, 1987). ERPs may be classified as exogenous or endogenous potentials (e.g., Donchin, Ritter and McCallum, 1978; Gaillard and Ritter, 1983). Exogenous potentials (such as N1) are obligatory responses. They are elicited any time stimuli with appropriate physical characteristics are presented, and their amplitudes and latencies are primarily determined by these physical stimulus parameters (e.g., Gaillard, 1988). Endogenous potentials (such as N2b and P3) are less directly affected by physical stimulus parameters; rather, these potentials are elicited when stimuli have psychological meaning to the subjects (e.g., Picton and Hillyard, 1988; Sutton, Braren and Zubin, 1965). The ERPs to be studied in this dissertation are described further below.

N1

The cortical auditory ERP N1 was first described by P.A. Davis (1939). N1 is an obligatory, exogenous potential that is elicited approximately 100 ms after acoustic stimulus onset. The N1 is preceded by the positive obligatory wave P1, and is followed by the obligatory positive wave P2 (which occurs approximately 200 ms after stimulus onset). P1 and P2 are not examined in this dissertation and will not be discussed further. N1 is generated in the vicinity of primary auditory cortex (e.g., Vaughan and Ritter, 1970). N1 varies with physical characteristics of the stimulus (e.g., Picton, Woods, Baribeau-Braun and Healey, 1977). Additionally, it is affected by attention (e.g., Näätänen and Picton, 1987) and by subject state, such as sleep (e.g., Osterhammel, Davis, Wier and Hirsh, 1973). N1 amplitude increases and latency decreases as stimulus intensity increases, though this relationship reaches an asymptote at high intensities in some individual subjects and also during rapid stimulus presentation (e.g., Davis and Zerlin, 1966; Keidel and Spreng, 1965; Picton, Rodriguez, Linden and Maiste, 1985). Response amplitude decreases with higher frequency stimuli (e.g., Antinoro and Skinner, 1968; Picton, 1990). Low-frequency tones elicit an N1 with large amplitude, whereas high-frequency tones elicit an N1 with smaller amplitude.

N1 can be elicited by many types of stimuli. It has, for example, been seen in response to tones (e.g., Picton, Woods and Proulx, 1978), to speech (e.g., Wood, 1975), to frequency glides (e.g., Arlinger, Elberling, Bak, Kofoed, Lebech and Saermark, 1982), to stimulus onset and offset (e.g., Davis and Zerlin, 1966), and to binaural and monaural stimuli (e.g., Davis and Zerlin, 1966).

N1 is not a unitary potential; rather, it comprises at least three components (e.g., McCallum and Curry, 1979, 1980; Näätänen and Picton, 1987). The first component of N1, as described by Näätänen and Picton (1987), is a frontocentral negativity. This component is generated by bilateral vertically oriented dipoles located in the auditory cortex on the superior temporal lobe. These authors hypothesized that this component may reflect the calling of attention to the availability of stimulus information, the reading out of sensory information from the auditory cortex, or the formation of a sensory memory of the stimulus within the auditory cortex. The second component, reflected by the "T-complex", is a positive wave occurring at a latency of 100 ms, followed by a negative wave occurring at a latency of 150 ms (Wolpaw and Penry, 1975). This component is generated in the auditory association cortex in the superior temporal gyrus. Due to a lack of data, Wolpaw and Penry did not propose a distinct function for this component. The third component described by Näätänen and Picton (1987) is a negative wave. This wave is maximal at the vertex, and has a latency of 100 ms. The generator of this wave is not known. Näätänen and Picton indicated that this component may reflect a widespread transient arousal which facilitates sensory and motor responses to the stimulus, resulting in more efficient functioning. Additionally, they proposed that the component may alert sensory association and motor cortex when a stimulus occurs after a period of "quiescence". Thus, the N1 comprises at least three components. Typical experimental paradigms, however, do not allow the components to be examined separately (Näätänen and Picton, 1987).

Some experiments (e.g., Hillyard and Kutas, 1983) have suggested that N1 is an index of the amount of signal information received by the sensory detecting system. It was the first ERP wave used to estimate hearing sensitivity. Differences between N1 threshold, the lowest stimulus intensity where the N1 wave is present, and behavioral threshold are frequently less than 20 dB

(e.g., Appleby, McDermick and Scott, 1963; Beagley and Kellogg, 1969; Cody and Bickford, 1965; Davis, 1966; Davis, Hirsh, Shelnott and Bowers, 1967; McCandless and Best, 1964; McCandless and Lenz, 1968; Mendel, Hosick, Windman, Davis, Hirsh, and Dinges, 1975; Perl, Galambos, Glorig and Thiede, 1953; Tyberghein and Forrez, 1971). Large discrepancies, however, have been reported (e.g., Prevek, Cernelc and Ribaric, 1976; Rapin, 1964; Rose, Keating, Hedgelock, Miller and Schreurs, 1972). The use of N1 to estimate hearing sensitivity in children was largely abandoned following the advent of the auditory brainstem response measures. Unlike N1, the auditory brainstem response (ABR) is insensitive to subject state. It provides reasonably accurate measures of threshold (e.g., Stapells, Gravel and Martin, 1995; Stapells, Picton and Durieux-Smith, 1994). The ABR does not, however, assess high-level auditory processing (i.e., beyond the level of the brainstem), and any relationship between the integrity of the pathways assessed by the ABR and higher level processing such as speech perception would be indirect at best. N1 is currently used in some clinical centers for the assessment of threshold in adult compensation cases and medicolegal patients (e.g., Hyde, Alberti, Matsumoto and Li, 1986).

In an oddball paradigm (e.g., 1000 Hz, 1000 Hz, 1000 Hz, 1000 Hz, 2000 Hz, 1000 Hz, etc.), infrequently occurring "deviant" stimuli (e.g., 2000 Hz) are embedded within a series of frequently occurring "standard" stimuli (e.g., 1000 Hz). Provided it is presented with appropriate physical parameters, each of these stimuli elicits an N1. The larger the frequency difference of the deviant stimulus relative to the standard stimulus, the larger the N1 to the deviant stimulus. Butler (1968) hypothesized that an increased N1 amplitude in response to deviant tones occurs because a different neuronal population is activated. The frequently occurring standard stimuli primarily activate neural populations specific to the frequency of the standard tones. These neuronal populations become refractory for several seconds. The number of nonrefractory neural populations activated by the deviant stimulus varies with the difference between its frequency and the frequency of the standard tones. When the frequency difference between the standard and deviant tones increases, a larger population of nonrefractory neurons can be activated. As a result,

the N1 elicited by the deviant stimulus is larger compared with the N1 elicited by the standard stimulus (Butler, 1968).

Mismatch Negativity

When stimuli are presented in an oddball paradigm, there is an increased negativity in response to the deviant sound that often begins during the N1 and usually lasts longer than N1. This negativity may appear as an enlarged N1, a second negative peak, or as an attenuation of the P2 wave (Picton, 1990). This wave, called the mismatch negativity (MMN), was first described by Näätänen, Gaillard and Mäntysalo (1978). The MMN is best seen by subtracting the response to stimuli presented as standards from the response to stimuli presented as deviants (Näätänen, 1990, p. 204). The MMN is an automatic response elicited by the "mismatch" or physical difference between the standard and deviant sounds. It is considered automatic because it can be elicited with or without attention or active participation by subjects (Näätänen, 1990, pp. 203, 205). It appears to be present in sleep (e.g., Alho, Sainio, Sajaniemi, Reinikainen and Näätänen, 1990; Csepe, Karmos and Molnar, 1987). The MMN is sensitive to changes in the acoustic properties of a stimulus, and may be elicited by changes in stimulus frequency (e.g., Sams, Paavilainen, Alho and Näätänen, 1985), intensity (e.g., Näätänen, Paavilainen, Alho, Reinikainen, and Sams, 1987), duration and timing (e.g., Näätänen, Paavilainen, and Reinikainen, 1989; Nordby, 1988), and location (e.g., Paavilainen, Karlsson, Reinikainen, and Näätänen, 1989). MMN amplitude increases and latency decreases as the physical difference between the standard and deviant stimuli increases (e.g., Näätänen and Gaillard, 1983). Additionally, amplitude increases as the number of standards before the deviant increases (e.g., Sams, Alho and Näätänen, 1983). Amplitude decreases as the interstimulus interval increases, up to about 10 seconds (e.g., Mäntysalo and Näätänen, 1987). Response amplitude is maximal at fronto-central scalp locations, though the MMN is also large at temporal scalp locations, reflecting its origin in the auditory cortex. MMN polarity inverts at the mastoids when a nose reference is used (e.g., Alho, Paavilainen, Reinikainen, Sams and Näätänen, 1986). The MMN is generated primarily in the vicinity of primary auditory

cortex (e.g., Alho, 1995; Scherg, Vasjar and Picton, 1989), though the location of the generators is different from that of N1 (e.g., Csépe, Pantev, Hoke, Hampson, and Ross, 1992; Scherg, Vasjar and Picton, 1989). The MMN appears to be specific to the auditory modality (e.g., Nyman, Alho, Laurinen, Paavilainen, Radil, Reinikainen, Sams and Näätänen, 1990), though the auditory MMN may be modulated by visual input (e.g., Sams, Aulanko, Hamalainen, Hari, Lounasmaa, Lu and Simola, 1991).

Ritter and Ruchkin (1992) reported that the MMN differs from other waves associated with stimulus discrimination (e.g., N2b, P3) in two important ways. First, the MMN can be elicited by predictable stimuli (e.g., Scherg, Vajsar and Picton, 1989). Second, it is elicited *both* by attended and by unattended stimuli (e.g., Näätänen, 1990).

At this time, the MMN is not used routinely in clinical audiology, though it may prove useful in the future as a marker of stimulus discrimination in difficult-to-test populations.

N2

When deviant stimuli embedded in a series of standard stimuli are consciously noted, another negative wave is superimposed on the MMN. This wave is referred to as N2 or N2b (e.g., Näätänen, Simpson, and Loveless, 1982). ["N2a" in the auditory modality is the MMN (Näätänen, Simpson and Loveless, 1982)]. N2b amplitude, like the MMN, is inversely related to the probability of the deviant stimulus (e.g., Squires, Squires and Hillyard, 1975). Its latency varies as with the magnitude of the physical difference between the standard and the deviant stimulus (e.g., Ritter, Simson, Vaughan and Friedman, 1979). N2b was first distinguished from the MMN using a selective attention experiment (Näätänen, Gaillard and Mäntysalo, 1978). N2b was present only in the attended condition whereas the MMN was present both in the attended and unattended condition. Unlike the MMN, N2b can be elicited by both stimulus matches (i.e., repetition of a stimulus) and mismatches (i.e., stimulus change) (e.g., Breton, Ritter, Simson, and Vaughan, 1988; Ritter, Paavilainen, Laurikainen, Reinikainen, Alho, Sams and Näätänen, 1992). In further contrast to the MMN, N2b requires unpredictable stimulus presentation. Also in contrast to the MMN, N2b is seen in both auditory and visual modalities (e.g., Simson, Vaughan and Ritter, 1976, 1977). N2b

occurs slightly later than the MMN, and has maximum amplitude at midline central electrode sites (e.g., Novak, Ritter, Vaughan and Wiznitzer, 1990; Sams, Aulanko, Aaltonen and Näätänen, 1990), somewhat posterior to the MMN. N2 reflects discrimination and classification of stimuli (e.g., Ritter, Simson, Vaughan and Macht, 1982).

As a result of the overlap in temporal characteristics between N2, N2b and the MMN, it is difficult to separate these waves without comparing waveforms obtained in an attend condition (MMN + N2b) with waveforms obtained in an ignore condition (MMN only). Additionally, the waves are differentiated using scalp distribution, and by manipulating the experimental paradigm.

P3

P3 is an endogenous, late, positive wave that typically occurs approximately 300 ms after stimulus onset, though its latency varies with experimental paradigm (e.g., Donchin, Ritter, McCallum 1978; Picton and Hillyard, 1988). It was first described by Sutton, Braren, Zubin and John (1965). Like N2, it is elicited by deviant stimuli presented in an oddball paradigm, when subjects pay attention to the stimuli and are engaged in an active discrimination task such as counting or pressing a button to the deviant stimuli (e.g., Pritchard, 1981). It can be elicited by a stimulus omission, if the omission is unpredictable and task-relevant (e.g., Simson, Vaughan and Ritter, 1976; Sutton, Tueting, Zubin and John, 1967). P3 is not elicited when deviant stimuli are predictable (Sutton, Braren, Zubin and John, 1965).

P3 comprises at least two components. P3a is more frontal in scalp distribution and is not affected by attention (Squires, Squires and Hillyard, 1975). It may signal the obtrusiveness of the deviant stimuli (e.g., Lang, Eerola, Korpilahti, Holopainen, Salo and Aaltonen, 1995), or a brief preconscious attention switch (e.g., Lyytinen, Blomberg, and Näätänen, 1992; Näätänen, 1995; Sams, Paavilainen, Alho and Näätänen, 1985). P3b is more parietal in scalp location, and is dependent on attention (e.g., Picton, 1992). As is typically employed in the literature, "P3" in this dissertation refers to P3b. P3 has multiple generators (e.g., Wood, Allison, Goff, Williamson, and Spencer, 1980). Contributions to P3 have been reported from frontal cortex (e.g., Courchesne,

1978), centroparietal cortex or hippocampus (e.g., Vaughan and Ritter, 1970; Pritchard, 1981), and auditory cortex (e.g., Richer, Johnson and Beatty, 1983).

P3 amplitude increases when the probability of the deviant stimuli decreases (e.g., Duncan-Johnson and Donchin, 1977; Fitzgerald and Picton, 1983; Squires, Squires and Hillyard, 1975; Sutton, Braren, Zubin and John, 1965). This is true for both the local probability of each individual deviant, and the global probability of all deviants across the run. Additionally, amplitude increases when confidence regarding task performance increases, and amplitude decreases when the discrimination task becomes more difficult (e.g., Fitzgerald and Picton, 1983; Hillyard, Squires, Bauer and Lindsay, 1971; Picton, 1992; Picton, Campbell, Baribeau-Braun, and Proulx, 1978; Squires, Squires and Hillyard, 1975).

P3 latency has been suggested to index stimulus evaluation time (e.g., Donchin, 1979; Kutas, McCarthy and Donchin, 1977), or to reflect post-decision evaluation of the deviant stimuli (e.g., Hillyard and Picton, 1987). The precise role of P3 in cognition is not known. P3 has a shorter refractory period than the earlier components (e.g., Woods, Hillyard, Courchesne and Galambos, 1980). As a result, it may index rapid, sequential decision making (Pritchard, 1981).

Many of the same factors influencing behavioral measures of processing time (i.e., reaction time) also affect P3 latency, although reaction time and P3 latency can be disassociated (e.g., Kutas, McCarthy and Donchin, 1977). Reaction time is determined both by the time it takes to evaluate a stimulus and by the time it takes to initiate and carry-out a motor response. Errors are more common when subjects are instructed to respond quickly, resulting in short reaction times. When a task is difficult, both P3 and RT increase in latency. The increase, however, is greater for RT (e.g., Fitzgerald and Picton, 1983). When subjects are instructed to respond to the deviant sound as quickly as possible, accuracy is traded for speed, and resulting correlations between P3 latency and RT are low. However, when subjects are instructed to respond to the deviant sound as quickly as possible while avoiding errors (i.e., place equal weight on speed and accuracy), correlations between P3 latency and RT are higher, and the error rate is lower than for the previous condition. In this case, RT is determined primarily by the time required for stimulus evaluation.

Evaluation of the stimulus must be completed before the processing responsible for P3 occurs (Kutas, McCarthy and Donchin, 1977). Evidence for this was obtained by Ritter (1978) who demonstrated that P3 is too late to be associated with decision-related processes.

1B. ERPs and Speech Perception

Both obligatory (N1) and discriminative (MMN, N2b, P3) cortical ERPs have been elicited using speech stimuli (e.g., Dorman, 1974; Friedman, Simson, Ritter and Rapin, 1975; Galambos, Benson, Smith, Schulman-Galambos and Osier, 1975; Gelfer, 1987; Grabow, Aronson, Offord, Rose and Greene, 1980; Hansen, Dickstein, Berka and Hillyard, 1983; Hink, Hillyard and Benson, 1978; Kraus, McGee, Micco, Sharma, Carrell and Nichol, 1993; Kraus, McGee, Sharma, Carrell and Nicol, 1992; Kurtzberg, Hilpert, Kreuzer and Vaughan, 1984; Lawson and Gaillard, 1981a; Lawson and Gaillard, 1981b; Novak, Kurtzberg, Kreuzer and Vaughan, 1989; Sams, Paavilainen, Alho and Näätänen, 1985; Wood, 1975; Wood, Goff and Day, 1971; Woods and Elmasian, 1986). Much of the literature on ERPs and speech perception focused on hemispheric dominance and lateralization issues (for review, see Molfese, Molfese and Parsons, 1983; Molfese and Betz, 1988), on categorical perception (e.g., Aaltonen, Niemi, Nyrke and Tuhkanen, 1987; Maiste, 1989; Molfese, 1978; Sams, Aulanko, Aaltonen, and Näätänen, 1985; Sharma, Kraus, McGee, Carrell and Nicol, 1993a), or on acoustic *versus* phonetic processing (e.g., Dorman, 1974; Sharma, Kraus, McGee, Carrell and Nichol, 1993b; Wood, 1975).

Most of the above studies have examined subjects with normal hearing sensitivity. Peripheral hearing loss often results in decreased speech perception ability due to decreased audibility and/or distortion of the speech sounds (see Chapter 1C: Effects of Hearing Loss on Speech Perception Chapter, below). It is therefore important to examine the effects of decreased audibility on ERPs to speech sounds in order to be able to use these ERPs with clinical populations. Knowledge of the effects of decreased audibility on ERPs to speech sounds may provide us with more information regarding how brain processing of speech is changed with hearing loss.

The effects of hearing impairment on ERPs elicited by speech stimuli have not been studied systematically. Limited work, however, using a hearing-impaired population exists. Kurtzberg

(1989) demonstrated changes in ERPs in an individual with the use of hearing aids. The speech sounds /da/ and /ta/ were presented at 90 dB peak-equivalent SPL to a 31-month-old child with a moderate to moderately severe sensorineural hearing loss. Without hearing aids, the child's obligatory ERPs were low in amplitude and poorly formed. Discriminative ERPs were absent. With hearing aids, the obligatory responses were well-formed and a clear discriminative wave was present.

Polen (1984) reported significantly longer latencies for N1, P2, N2 and P3, and smaller amplitudes for P2 and N2 in a group of hearing-impaired listeners compared to normal listeners on a /v/-/f/ contrast. Wall, Dalebout, Davidson and Fox (1991) found that only N1 amplitudes were significantly different between normal and hearing-impaired groups for /bɛ/-/dɛ/ and /bɛ/-/pɛ/ contrasts. Because this latter study employed only five listeners in each group, results must be interpreted cautiously.

Kurtzberg and colleagues examined changes in obligatory potentials with amplification in a large and diverse group of children with hearing loss. Results showed that there is large variability in the audiometric configurations associated with a present obligatory cortical response (Kurtzberg, 1991; Stapells, Kurtzberg, Martin, Gravel and Kreuzer, in preparation).

Two published studies have examined ERPs to speech sounds in patients with cochlear implants. Kaga, Koderu, Hirota and Tsuzuku (1991) measured P3 to tones and to spoken Japanese words in a 20-year-old subject. The subject was tested three months and six months after cochlear implantation. A small P3 was present for both types of stimulation three months after implantation. Six months after implantation, however, P3 morphology was reportedly clearer for both stimuli. Another study (Kraus, Micco, Koch, McGee, Carrell, Sharma, Wiet and Weingarten, 1993) examined the MMN in eight "good" cochlear implant subjects and one "poor" implant subject. The speech sounds used were /da/ and /ta/ presented at 65 - 70 dB SPL. The MMN was present in all eight "good" users, but not in the "poor" user. MMN latencies and morphology for the "good" users were similar to results for a normal-hearing group.

Much work remains to be done in the area of ERPs and speech perception, especially

concerning the effects of hearing loss. ERPs provide a means of measuring the timing and sequence of speech sound processing. Therefore, they may provide knowledge of how the timing and sequencing of speech-sound processing is altered with hearing loss. Additionally, it is possible to evaluate the spatial distribution of the ERPs. It would be interesting to know if the scalp distribution of ERPs to speech sounds is altered in patients with hearing loss, either due to the hearing loss itself, or possibly due to plastic brain changes that occur with hearing loss. ERPs might provide information on whether speech sounds are audible or discriminable. Knowledge of this latter information is especially important in populations where behavioral assessment of speech perception is difficult, such as infants. This information could be helpful for hearing aid fitting and monitoring, for assessing (re)habilitation, and for determining cochlear implant candidacy and efficacy in young children.

1C. Effects of Hearing Loss on Speech Perception

In contrast to ERP measures, the effects of decreased audibility on behavioral measures of speech perception performance are reasonably well known (for reviews, see: Boothroyd, 1978; Walden, 1984). This literature suggests that a large portion of the speech perception difficulties of hearing-impaired listeners is related to loss of audibility (e.g., Boothroyd, 1984; Erber, 1972; Erber, 1974; Humes, 1988; Smith, 1975; Yoshioka and Thornton, 1980; Zurek and Delhorne, 1987). Hearing loss configuration also affects the probability of speech recognition (Bilger and Wang, 1976; Dubno, Dirks and Langhofer, 1982; Owens, Benedict and Schubert, 1972). The perception of consonant place of articulation contrasts tends to be particularly susceptible to the effects of hearing loss (e.g., Boothroyd, 1984; Dubno, Dirks and Ellison, 1989; Dubno, Dirks and Langhofer, 1982; Gordon, 1987; Walden, 1984). The effects of sensorineural impairment, however, are not limited solely to audibility (e.g., Festen and Plomp, 1983; Scharf, 1978; Thibodeau, 1991). Other effects may include widened critical bands, decreased frequency selectivity, altered temporal integration times, recruitment, and other problems of sound processing. For this reason, speech perception is often studied in normal listeners using noise masking (e.g., Bell, Dirks and Carterette, 1989; Fabry and Van Tasell, 1986; Humes, Dirks, Bell and Kinkaid, 1987) or filtering of stimuli to

control for audibility in specific spectral regions (e.g., Bell, Dirks and Carterette, 1989; Dubno, Dirks and Ellison, 1989; Fabry and Van Tasell, 1986; French and Steinberg, 1947; Kryter, 1960; Miller and Nicely, 1955; Owens, Benedict and Schubert, 1972; Pollack, 1948; Sher and Owens, 1974; Walden, Schwartz, Montgomery and Prosek, 1981; Wang, Reed and Bilger, 1978). These methods allow one to control for some of the variability seen when testing hearing-impaired listeners (due to factors that are more difficult to control such as widened critical bands, decreased frequency selectivity, altered temporal integration times, etc.). Use of spectrally shaped masking noise produces threshold elevations which are primarily cochlear in origin and also simulates the loudness recruitment typically found in sensorineural hearing loss (e.g., Humes, Dirks, Bell and Kincaid, 1987; Humes and Roberts, 1990).

Relevant to the studies herein are early studies of speech perception that examined the effects of filtering of stimuli on speech recognition. French and Steinberg (1947) examined syllable recognition as a function of the cutoff frequency of low-pass and high-pass filtering of the speech stimuli. The effects of stimulus intensity and masking on the articulation index were also examined. Results indicate that, when examining the functions displayed on a graph of filter cutoff setting *versus* speech recognition (French and Steinberg, 1947, figure 12), the crossover point of the functions (the intersection point on the graph of the results of the low-pass and high-pass filtering conditions) for low-pass and high-pass filtered speech occurs at approximately 1800 Hz. This indicates that half of the spectral information important for speech perception occurs below 1800 Hz and half falls above 1800 Hz. In this dissertation, both behavioral and ERP crossover points obtained will be calculated and compared to each other and to the literature.

Pollack (1948) extended the work of French and Steinberg, and examined speech recognition in white noise as a function of the filter settings used to filter the speech sounds, as well as by examining the interactions of low-frequency and high-frequency information on speech recognition. The intensity of the speech was varied, as well as the frequencies passed by the filter. Results indicated that speech recognition increased as stimulus intensity increased (hence signal-to-noise ratio) and as the bandwidth of speech passed by the filters increased. High frequencies alone

(e.g., >2000 Hz) contributed little to speech recognition. When low frequencies were also passed, however, the high frequencies made a large contribution to recognition. When low frequencies were presented alone, recognition increased slowly as intensity increased. As much as a 40-dB increase in intensity was required in order for recognition to reach a maximum. When high frequencies were presented alone, there was a rapid increase in speech recognition as presentation level increased. Scores reached a maximum at about 15 dB above threshold. Pollack concluded that when listening in noise, it is easier to compensate for a loss of low frequencies by an increase in gain than for a proportionate loss of high-frequency information (Pollack, 1948). This is due, in part, to upward spread of masking and to the weaker energy of the higher frequency sounds. White noise, therefore, will mask the high-frequency speech sounds before having an effect on the more intense, low-frequency speech sounds.

Miller and Nicely (1955) examined consonant confusion matrices obtained by presenting consonant-vowel (CV) combinations under various high-pass and low-pass filtering (of stimuli) conditions, and in a series of different signal-to-noise ratios produced using broadband noise masking. Of interest to the present studies are their findings that low-pass filtering of the stimuli (which has a similar effect on audibility to that of high-pass noise masking) had the greatest effect on consonant place perception, followed by the perception of duration and affrication. The recognition of voicing and nasality contrasts were affected least by low-pass filtering. High-pass filtering of the stimuli (which has a similar effect on audibility to that of low-pass noise masking) caused the perception of all features (except for duration) to deteriorate as low frequencies were progressively removed (Miller and Nicely, 1955). They concluded that audibility is the primary difficulty when speech is high-pass filtered (i.e., speech is not audible), and that consonant confusions are the primary difficulties when speech is low-pass filtered (i.e., although some of the speech energy is audible, discrimination between different consonants is difficult). The crossover point dividing the frequency scale into segments that contribute equally to speech recognition of all sounds together was approximately 1550 Hz. The crossover point specifically for consonant place was approximately 1900 Hz.

Kryter (1960) examined speech recognition as a function of filtering and signal-to-noise ratio. Results indicated that when speech is passed through one channel of a 3-channel filter system, with each channel passing information in a 500-Hz-wide band (e.g., 1000-Hz center frequency = 750-1250 Hz bandpass), the spectral region centered around 1600 to 1700 Hz contributes the most to speech recognition. When speech is passed through two channels, greatest recognition is achieved when one passband is centered at 500 or 750 Hz, and the other at 1500 - 1750 or 2500 - 2700 Hz (the bands were 500 - 1500 Hz for band 1, and 1000 - 3000 Hz for band 2). When speech is passed through three channels, performance was best when one band was centered around 500 Hz, another around 1500 Hz, and the third band around 2500 Hz. The pattern of results suggest that when spectral regions containing the steady-state formant frequencies and the formant transition frequencies are passed, recognition is high. Additionally, results indicate that when multiple bands separated in frequency are passed, performance is better than when contiguous bands are passed. An implication of Kryter's results for the present studies are that when spectral regions containing steady-state formant frequencies and formant transition frequencies are masked, recognition will deteriorate.

Subsequent research compared the performance of normal-hearing subjects listening to filtered speech to that of listeners with sensorineural hearing losses with comparable audiometric configurations. Owens, Benedict and Schubert (1972) compared phoneme recognition scores between listeners with sensorineural hearing loss of various configurations as well as with normals listening to stimuli filtered by a 780-Hz low-pass filter. In terms of error probabilities, they found that listeners with sharply sloping hearing losses performed similarly to the normal listeners listening to filtered stimuli. Performance for the normal listeners, however, was poorer for /s/, /j/, /tʃ/, and /dʒ/, perhaps because the slope of the decreased audibility function was steeper for the normal-hearing group than for the hearing-impaired group. Thus, with the exception of four phonemes, filtering resulted in similar error probabilities for the normal group compared with the hearing-impaired subjects.

Sher and Owens (1974) studied phoneme recognition in two groups of subjects. One group had sensorineural hearing loss above 2000 Hz. The other group had normal hearing and listened to the same phonemes low-pass filtered at 2040 Hz. The study found no significant differences between groups in overall scores, probability of error for individual phonemes, or in the types of error substitutions made.

Wang, Reed and Bilger (1978) compared the effects of high-pass and low-pass filtering and sensorineural hearing loss on patterns of consonant confusions. Results indicated that steep low-pass filtering results in consonant confusions similar to those of listeners with high-frequency hearing loss. In contrast, steep high-pass filtering results in consonant confusions that are similar to those of listeners with flat or rising audiograms. Results were explained based on the spectrum level of speech heard by the subjects.

Walden, Schwartz, Montgomery and Prosek (1981) examined the extent to which the effects of hearing loss on consonant recognition could be simulated by a filter. Part of their study examined listeners with unilateral hearing loss. The audiometric configuration of the impaired ear was matched in the normal-hearing ear using a spectrum shaper. Results indicated that matching the audiometric configuration does not adequately simulate the effect of sensorineural hearing loss on overall consonant recognition (e.g., percent correct for all of the consonants collapsed into one analysis) or on the recognition of individual consonants (e.g., for /p/ alone). However, it does simulate the effects of hearing loss on patterns of feature recognition (e.g., both the impaired ear and the normal ear with speech filtered using the spectrum shaper performed poorly on consonant place recognition but well on nasality).

More recent studies have examined the effects of filtering, masking, and a combination of methods, on speech recognition and have compared findings with the performance of listeners with sensorineural hearing loss. Milner (1982) examined speech recognition in normal-hearing listeners listening in quiet, normal-hearing listeners listening in shaped white noise to simulate sensorineural hearing loss, and listeners with sensorineural hearing loss. He presented low-pass, high-pass or bandpass filtered speech to the subjects at five presentation levels ranging from near threshold to

near discomfort. He found that speech recognition was high if the speech was high-pass filtered at 700 Hz or low-pass filtered at 2800 Hz, provided that the speech stimuli were clearly audible. Performance of the normal-hearing listeners with simulated hearing losses were similar to listeners with flat sensorineural hearing loss.

Fabry and Van Tasell (1986) examined speech recognition in listeners with unilateral hearing loss. The audiometric configuration of the hearing-impaired ear was matched in the normal-hearing ear using masking or using filtering of stimuli. For three subjects, both masking and filtering adequately simulated the effects of hearing loss on error patterns for consonant features. For one subject, only filtering adequately simulated the effects of sensorineural hearing loss. In remaining two subjects, however, neither filtering nor masking was adequate. The authors concluded that the primary effect of sensorineural hearing loss in some subjects is the attenuation of speech cues resulting from decreased hearing thresholds. Results were interpreted as providing partial support for the use of normal subjects listening to filtered stimuli in order to assess the effects of decreased audibility on speech recognition, as filtering was adequate in four of six subjects.

Humes, Dirks, Bell and Kincaid (1987) studied speech recognition in four hearing-impaired subjects and in three groups of normal-hearing subjects listening in spectrally shaped masking noise designed to produce masked thresholds identical to one of the hearing-impaired subjects. Two of the four hearing-impaired subjects performed better than the corresponding masked-normal listeners in terms of overall percent correct recognition. The other two hearing-impaired subjects performed similarly to the corresponding masked normal listeners. The authors performed a gross analysis of the errors made by the hearing-impaired and normal listeners, and reported that the types of errors made were different. The authors did not elaborate on the nature of this difference.

Bell, Dirks and Carterette (1989) examined the effects of low-pass filtering of stimuli, shaped masking noise, stimulus intensity, and consonant position (i.e., initial *versus* final) on consonant confusion patterns in normal listeners. Results indicated that all of these factors affect consonant

confusion patterns and overall recognition scores. Additionally, intensity interacted with filtering and consonant position on consonant confusion patterns. At low stimulus intensities, filtering had no effect on the audible speech spectrum. As stimulus intensity increased, however, the influence of the filter increased.

Dubno, Dirks and Ellison (1989) studied the contributions of various frequency regions on the perception of consonant place of articulation in normal listeners and in listeners with high-frequency hearing loss. Presentation level, and high- and low-pass filtering of the stimuli were varied systematically. Differences in consonant recognition and error patterns between the two groups were seen in the low-pass filtering condition when the stimulus bandwidth included regions where threshold was elevated for the hearing-impaired listeners. The authors hypothesized that this finding may have been due to filter slopes that did not adequately match the configuration of the hearing-impaired group, and differences in sensation level for portions of the signal that are important for place perception between the two groups. Additionally, modeling of changes in audibility and loudness growth in sensorineural hearing loss may have been inadequate and/or additional factors beyond audibility may contribute to consonant recognition and error pattern in hearing-impaired listeners. Of interest to this dissertation, recognition of /b/ was poorest when the low frequencies were significantly filtered, whereas recognition of /d/ was poorest when high-frequency regions were filtered.

Portions of the work of Thornton and Abbas (1980) are applicable to the proposed studies. Their study examined four subjects with low-frequency sensorineural hearing loss to determine whether responses to low-frequency stimuli might be due to stimulation of higher characteristic frequency nerve fibers. In fact, this was the case in three subjects. Of particular interest for the proposed studies, a group of normal listeners and three of the hearing-impaired subjects were presented with high-pass, low-pass, and unfiltered speech in quiet and in the presence of a high-pass noise masker. Both the speech and the noise were presented at an intensity of 80 dB HL (signal-to-noise ratio = 0). The normal listeners performed well in the broadband noise condition (median recognition = 96%). When speech was high-pass filtered at 3000 Hz, performance was

poor (median recognition = 32%). The normal listeners performed moderately well for speech low-pass filtered at 1500 Hz (median recognition = 78%) and for low-pass filtered speech presented in the presence of a 1500 - 8000 Hz noise band (median recognition = 80%). Performance for the hearing-impaired listeners in the broadband noise condition was poorer than that of the normal listeners (recognition performance ranged from 56-88% correct). In contrast, performance in the high-pass filtered condition (36-46% correct) was comparable to that of the normal listeners. This was the region of normal hearing sensitivity for the hearing-impaired listeners. Their hearing loss occurred only for low frequencies. Performance was poorer for the hearing-impaired listeners than for the normal listeners in the low-pass filtered (12-20% correct) and noise-masked low-pass filtered (0-22% correct) conditions.

The portion of these studies that is of interest for this dissertation is the performance of the normal listeners in the high- and the low-pass filtered speech conditions. Recognition scores were high in the broadband (unfiltered) condition (96% correct), fairly high in the low-pass filtered speech condition (78% correct), but poor (32% correct) in the high-pass filtered speech condition. This suggests that when high-frequency information relevant to speech is removed, recognition performance is adversely affected. Removal of low-frequency information does not result in the same degree of decrement in speech recognition.

Dubno and Ahlstrom (1995) examined tonal thresholds and speech recognition in low-pass masking noise for listeners with normal hearing, for listeners with normal hearing with simulated hearing loss produced by spectrally shaped noise masking, and for hearing-impaired listeners. In general, there were no consistent differences between speech recognition scores in low-pass noise for hearing-impaired and normal-hearing listeners with simulated hearing loss. Also, speech recognition was highest for conditions where more of the speech spectrum was audible. In other words, it was highest for conditions with higher speech intensities, lower masking levels, and lower masker cutoff frequencies.

In summary, speech recognition has been assessed in normal listeners using masking noise and filtering in order to simulate decreased audibility in specific controlled spectral regions, and performance has been compared to listeners with sensorineural hearing loss. Patterns of performance between the normal listeners and those with hearing loss are similar in many cases, thereby justifying the use of such techniques.

Chapter 2

PURPOSE AND SIGNIFICANCE OF THE DISSERTATION STUDIES

2A. Rationale

As the literature review in Chapter 1 demonstrates, the effects of decreased audibility for specific spectral regions on behavioral and cortical ERP measures to speech sounds have yet to be systematically evaluated.

The speech sounds examined in this dissertation are /ba/ and /da/. They were selected because perception of place of articulation contrasts tends to be difficult for listeners with hearing loss. Discrimination of the /ba/-/da/ contrast used for these studies is based primarily on differences in the second and third formant frequency transitions. Hearing loss typically occurs in high-frequency spectral regions, where the speech energy comprising these formant transitions is located. Masking of these frequency regions will result in changes in the ability to discriminate the /ba/-/da/ contrast.

Noise masking of normal listeners was used so that audibility factors could be better controlled than is possible for hearing-impaired listeners. Also, spectrally shaped noise masking allows for use of the high-pass noise derived response technique (e.g., Don and Eggermont, 1978) to examine cochlear contributions to the ERPs (see Chapter 4). High-pass noise masking was selected because decreased audibility associated with sensorineural hearing loss typically occurs for high-frequency spectral regions. Low-pass noise masking was selected because decreased audibility associated with sensorineural hearing loss does not *always* occur only in high-frequency spectral regions. Low-frequency regions may be affected as well. The use of high-pass noise masking raises thresholds for frequencies above the filter cutoff settings. The use of low-pass noise raises thresholds for frequencies at and below the filter cutoff settings, and even above due to upward spread of masking.

Behavioral Measures of Speech Perception

The behavioral measures examined in this dissertation are sensitivity (d') and reaction time (RT). The d' score [$d' = z(\text{false alarm}) - z(\text{hit})$] is a measure of percent correct that takes into account the false alarm rate (Hochhaus, 1972; Swets, 1964; Swets, 1973; Yanz, 1984). To this author's

knowledge, no published studies have examined reaction time and recognition performance (hits, d') for /ba/ versus /da/ in normal-hearing listeners using systematically varied high-and low-pass noise masking. These dissertation studies, therefore, will expand our knowledge of ERPs and behavioral speech perception. Reaction times provide a metric of processing difficulty or ease of listening by measuring the speed of processing (e.g., Downs, 1982; Downs and Crum, 1978). Previous studies have demonstrated that reaction times to speech sounds are increased when speech is presented in broadband noise, speech-weighted noise, or in multi-talker babble (e.g., Downs and Crum, 1978; Gatehouse and Gordon, 1990; Hecker, Stevens and Williams, 1966). Both RT and d' measures assess how well a subject can perform a task.

ERP Measures of Speech Perception

The ERPs examined in this dissertation are N1, MMN, N2 and P3. ERPs can provide information on the timing, sequence, and scalp distribution (from which intracranial generators can be inferred) of speech sound processing. Use of these ERPs allows for examination of auditory processing at different processing stages. N1 is the earliest wave studied. It is generated in the vicinity of primary auditory cortex (e.g., Scherg, Vajsar and Picton, 1989; Vaughan and Ritter, 1970). N1 is present when audible stimulus energy is present, whether or not subjects are paying attention to the sounds (e.g., Näätänen and Picton, 1987). N1 allows for examination of brain processing of stimuli beginning as early as 80 ms after stimulus onset. The MMN begins during the N1 and can last longer than N1. The MMN is also generated mainly in the vicinity of primary auditory cortex (e.g., Alho, 1995; Javitt, Steinschneider, Schroeder, Vaughan and Arezzo, 1994; Scherg, Vasjar and Picton, 1989), though the location of the generators is different than N1 (e.g., Csépe, Pantev, Hoke, Hampson, and Ross, 1992; Scherg, Vasjar and Picton, 1989). It is present when audible stimuli are discriminable, whether or not the subjects are paying attention to the sounds. It also may be present when stimuli are not quite behaviorally discriminable (such as in a missed deviant) (Sams, Paavilainen, Alho and Näätänen, 1985). It therefore indexes speech sound discrimination at a preconscious level, and provides a window into additional processing of the stimulus that begins after the onset of N1. N2b overlaps with the MMN, and is present when

sounds are discriminable, provided the subject is paying attention and the sounds are task-relevant. It therefore provides an index of conscious sound discrimination. Finally, P3 follows N2b. Like N2b, it indexes conscious speech sound discrimination. It has multiple subcortical generators (e.g., Wood, Allison, Goff, Williamson, and Spencer, 1980); contributions to P3 have been reported from frontal cortex (e.g., Courchesne, 1978), centroparietal cortex (e.g., Vaughan and Ritter, 1970; Pritchard, 1981), and auditory cortex (e.g., Richer, Johnson and Beatty, 1983). P3 provides a window into speech sound processing beginning approximately 300 ms (or later) after stimulus onset.

Conditions where subjects paid attention to the stimuli (active discrimination) or ignored the stimuli (passive condition) were both employed in these dissertation studies. The information derived from these conditions is different. In conditions where subjects pay attention to stimuli, the obligatory N1 response is seen, as well as the discriminative MMN, N2b and P3 responses. Because the active condition requires the subject to pay attention, it is possible to collect behavioral measures of discrimination of the /ba/ and /da/ stimuli in the various noise masking conditions simultaneously with the collection of the ERPs. In an ignore condition, the obligatory N1 response is again obtained, but this time the MMN serves as the discriminative response. The ignore condition is required to evaluate the MMN without contamination by N2b. Although present, in an attend condition MMN is overlapped by the N2b response (N2). The ignore condition is also important because it does not require active participation by the subjects, and may therefore prove useful for future application with difficult-to-test populations, such as infants, who cannot cooperate for active discrimination tasks.

Use of Simultaneous Behavioral and ERP Measures of Speech Perception

The active discrimination condition in this dissertation allows for the simultaneous collection of both behavioral and ERP measures of speech perception. Neville and colleagues have suggested that ERPs are most useful when obtained in conjunction with behavioral measures, so that interpretation of behavioral and neurophysiological data are "mutually constrained" (Neville, Coffey, Holcolm and Tallal, 1991) which allows a direct comparison of the behavioral measures of

discrimination with the ERP measures. In the present studies, it is expected that high d' scores will be reflected in large ERP amplitudes, and low d' scores will be reflected in small ERP amplitudes. Similarly, it is expected that short RTs will be reflected in short ERP latencies, and long RTs will be reflected in long ERP latencies. If results indicate that behavioral and ERP measures are affected similarly by decreased audibility, then ERPs alone could be used as probes of speech perception ability.

2B. Implications

The dissertation studies have implications in terms of both basic research and clinical applications. Little research to date has examined the effects of hearing loss on ERPs. Results of these studies will show the effects of decreased audibility on N1, MMN, N2 and P3 and also on behavioral measures. The results provide insight into changes in neural activity and timing caused by decreased audibility, such as increased latencies and decreased amplitudes, thereby providing a better understanding of neural processes that may be altered in individuals with sensorineural hearing loss. For example, if decreased audibility results in increased latencies, and decreased amplitudes, this suggests that processing of speech may be slower in persons with hearing loss, and that the strength of processing is altered as well. These factors may be relevant to the poor speech perception performance of some hearing-impaired listeners and for future remediation. This dissertation will also provide more insight into potential clinical application of the N1, MMN, N2 and P3 ERPs as objective markers of audibility and auditory discrimination. The studies are a prerequisite to the application of these potentials to the clinical assessment of cortical responsivity to, and discrimination of, speech in hearing-impaired populations. Controlled assessment of the effects of decreased audibility in specific spectral regions may suggest appropriate testing parameters to use with hearing-impaired subjects and assist in the interpretation of responses from hearing-impaired subjects.

It is often difficult to obtain reliable measures of speech discrimination in young and/or hearing-impaired children due to cognitive immaturity, language deficits, auditory inexperience and behavioral/cooperational limitations. Boothroyd (1991) discussed the potential value of an

"objective" test of speech perception capacity for young hearing-impaired children that examined differences in evoked potentials to speech pattern contrasts. Because a passive ERP paradigm was included in this dissertation, the tests used may have direct applicability with pediatric and difficult-to-test patients where behavioral testing and active evoked potential paradigms are difficult (Alho, Sainio, Sajaniemi, Reinikainen, and Näätänen, 1990; Kurtzberg, 1989). ERP measures have potential application for hearing aid evaluation, for cochlear implant evaluation and as a measure of progress in aural (re)habilitation.

2C. Purpose of the Dissertation Studies

The purpose of the dissertation studies was to examine the effects of decreased audibility produced by spectrally shaped noise masking on cortical ERPs to speech sounds /ba/ and /da/. The dissertation comprises seven chapters containing a series of studies on the effects decreased audibility produced by high- and low-pass noise masking on cortical ERPs to speech sounds /ba/ and /da/. In addition, results of the studies will be integrated in a summary paper that follows. The summary paper examines the contributions of selected frequency regions to behavioral (d' , RT) and electrophysiological responses (N1, MMN, N2, P3) to /ba/ and /da/. Results for behavioral and ERP measures are compared and contrasted. Together, the dissertation studies will provide the first systematic investigation of the effects of decreased audibility on cortical auditory ERPs.

Chapter 3

The effects of decreased audibility produced by high-pass noise masking on cortical auditory event-related potentials to speech sounds /ba/ and /da/.

3A. ABSTRACT

This study investigated the effects of decreased audibility produced by high-pass noise masking on cortical ERPs (N1, N2, P3) to the speech sounds /ba/ and /da/ presented in an oddball paradigm at intensities of 65 and 80 dB SPL. Normal hearing subjects pressed a button in response to the deviant sound. Broadband masking noise was presented at an intensity sufficient to completely mask the response to the 65 dB SPL speech sounds, and subsequently high-pass filtered at 4000, 2000, 1000, 500, and 250 Hz. With high-pass masking noise, pure-tone behavioral thresholds increased by an average of 38 dB at the high-pass cutoff and by 50 dB one octave above the cutoff frequency. Results show that as the cutoff frequency of the high-pass masker was lowered, ERP latencies to speech sounds increased and amplitudes decreased. The cutoff frequency where these changes first occurred and the rate of the change differed for N1 compared to N2, P3, and the behavioral measures. N1 showed small systematic changes as the masker cutoff frequency was lowered. N2, P3, and behavioral measures showed marked changes below a masker cutoff of 2000 Hz. These results indicate that the decreased audibility resulting from the noise masking affects the various ERP components in a differential manner. N1 is related to the presence of audible stimulus energy, being present whether audible stimuli are discriminable or not. In contrast, N2 and P3 were absent when the stimuli were audible but not discriminable (i.e., when the second formant transitions were masked), reflecting stimulus discrimination. These data have implications regarding the effects of decreased audibility on cortical processing of speech sounds and for the study of cortical ERPs in populations with hearing impairment.

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3B. Introduction

Both obligatory (N1) and discriminative (N2, P3) cortical event-related potentials (ERPs) have been elicited using speech stimuli (e.g., Dorman, 1974; Galambos, Benson, Smith, Schulman-Galambos and Osier, 1975; Hink, Hillyard and Benson, 1978; Kraus, McGee, Sharma, Carrell, and Nicol, 1992; Kurtzberg, Hilpert, Kreuzer and Vaughan, 1984; Novak, Kurtzberg, Kreuzer, and Vaughan, 1989; Sams, Paavilainen, Alho and Näätänen, 1985; Wood, 1975; Wood, Goff and Day, 1971). Much of the literature in the area of ERPs and speech perception has focused on hemispheric dominance and lateralization issues (for review, see Molfese, Molfese and Parsons, 1983; Molfese and Betz, 1988), on categorical perception (e.g., Aaltonen, Niemi, Nyrke and Tuhkanen, 1987; Maiste, Wiens, Hunt, Scherg and Picton, 1995; Molfese, 1978; Sams, Aulanko, Aaltonen and Näätänen, 1985; Sharma, Kraus, McGee, Carrell and Nicol, 1993a), or on acoustic versus phonetic processing (e.g., Dorman, 1974; Sharma, Kraus, McGee, Carrell and Nichol, 1993b; Wood, 1975). The effects of hearing impairment on ERPs elicited by speech stimuli, however, are few (Polen, 1984; Wall, Dalebout, Davidson and Fox, 1991), and the effects of various hearing impairments have not been studied systematically. A few studies of hearing-impaired listeners have demonstrated changes in ERPs to speech stimuli with hearing aids (Kurtzberg, 1989) or cochlear implants (Kaga, Koderä, Hirota and Tsuzuka, 1991; Kraus, Micco, Koch, McGee, Carrell, Sharma, Wiet and Weingarten, 1993), but these studies generally examined small numbers of subjects. Data in our laboratories from children with hearing loss showed large variability in the audiometric configurations associated with a present cortical response (Stapells, Kurtzberg, Martin, Gravel and Kreuzer, in preparation).

In order to use the cortical ERPs clinically, it is important to determine the effects of decreased audibility on the obligatory and discriminative potentials. Cortical ERPs may be useful in demonstrating suprathreshold discrimination (such as speech, frequency, and temporal

discrimination) in difficult-to-test populations such as infants. In addition to measures of speech discrimination ability, the potentials might be used to measure the benefit from hearing aids, cochlear implants or other habilitation strategies. Thus, further research is needed in order to gain a better understanding of the effects of hearing loss on N1, N2 and P3 to speech sounds using well-controlled groups of subjects in order to carefully examine the effects of different degrees and configurations of hearing loss.

The effects of decreased audibility on behavioral measures of speech perception performance are reasonably well known (for reviews, see Boothroyd, 1978; Walden, 1984). The perception of place of articulation contrasts tends to be particularly susceptible to the effects of hearing loss (e.g., Boothroyd, 1984; Dubno, Dirks and Langhofer, 1982; Dubno, Dirks and Ellison, 1989; Gordon, 1987; Walden, 1984). Typical methods used to examine the effect of decreased audibility on speech perception performance are to use normal-hearing listeners and to progressively filter or mask specific spectral regions and then examine patterns of performance (e.g., Dubno, Dirks and Ellison, 1989; Fabry and Van Tasell, 1986; Humes, Dirks, Bell and Kincaid, 1987; Miller and Nicely, 1955; Sher and Owens, 1974; Walden, Schwartz, Montgomery and Prosek, 1981; Wang, Reed and Bilger, 1978). Another method is to use hearing-impaired listeners with various audiometric configurations and to compare performance across groups (e.g., Bilger and Wang, 1976; Dubno, Dirks and Langhofer, 1982; Reed, 1975; Walden and Montgomery, 1975). The effects of sensorineural impairment, however, are not limited solely to audibility (e.g., Fabry and Van Tasell, 1986; Festen and Plomp, 1983; Scharf, 1978; Thibodeau, 1991). For example, processing of frequency, intensity and temporal information may be affected. Therefore, studies using listeners with sensorineural hearing loss may show increased variability due to these additional effects of sensorineural hearing loss that are difficult to control.

In order to study the effects of controlled threshold elevations in specific spectral regions, with less of the variability present in sensorineural populations, we used high-pass noise-masked normal listeners. The data obtained from studies of noise-masked normal listeners may be useful in determining the optimal ERP parameters to apply to hearing-impaired listeners and may aid in

the interpretation of their data. The purpose of this study was to investigate the effects of decreased audibility produced by high-pass noise masking on the cortical obligatory N1, and the discriminative N2 and P3 ERPs to the speech sounds /ba/ and /da/ and their relationship to behavioral measures of discrimination.

3C. METHOD

Subjects

Ten normal-hearing adults (5 males and 5 females), aged 18 to 37 years (mean = 27 years) with no history of neurological disorder, participated. All subjects had hearing sensitivity of 20 dB HL (ANSI, 1969) or better from 250 through 4000 Hz bilaterally. Additionally, immittance testing was performed prior to each session in order to rule out changing middle ear function. All subjects had normal tympanograms and present ipsilateral acoustic reflexes at 1000 Hz in the test ear. Subjects signed consent forms after being informed of the nature of the experiment, and were paid for their participation.

Stimuli

The stimuli /ba/ and /da/ were selected for this study as they differ in place of articulation and thus in the frequency domain. The /ba/ and /da/ stimuli were created by digitizing natural tokens produced by a male talker. The tokens were then processed using linear prediction coefficient (LPC) analysis, and synthesized stimuli were regenerated using the LPC polynomial roots. The stimuli were digitized using a 30,000 Hz sampling rate (Neuroscan STIM; 12 bits; 10,000 Hz low-pass anti-aliasing filter, 12 dB/octave), edited to 150 ms duration by eliminating the final portion of the steady-state vowel and windowing the offset of the vowel, and calibrated in peak-to-peak equivalent SPL (dB ppe SPL). The acoustic waveforms of the speech stimuli, the wideband spectrograms and a schematic of the spectrograms showing the frequencies of the first three formants and the formant transitions are displayed in Figure 1 (see Figure 1). The stimuli differed primarily in second and third formant transition frequencies. The frequencies of the steady-state portion of the vowels were: F0 = 108 Hz, F1 = 674 Hz, F2 = 1140 Hz, and F3 = 2350 Hz. The

transitions for /ba/ began at 328 Hz for F1, 1071 Hz for F2, and 2298 Hz for F3; the transitions for /da/ began at 362 Hz for F1, 1832 Hz for F2, and 2540 Hz for F3. The burst frequencies were similar for the two speech sounds (1500–4800 Hz for /ba/; 1200–4900 Hz for /da/). Thus, the largest differences between the stimuli are in the 1000 to 2000 Hz range. The stimuli were delivered at a D/A rate of 30,000 Hz (10,000 Hz anti-imaging filter, 12 dB/octave), and presented to the right ear of the subjects at 65 and 80 dB ppe SPL using 200 stimuli per run. Subjects heard all 200 stimuli in a single run, and each condition was replicated yielding a total of 400 stimuli. Stimuli were presented in an oddball paradigm (e.g., /ba, ba, ba, ba, da, ba/, etc.) whereby stimuli presented as standards (e.g., /ba/) had .80 probability and stimuli presented as deviants (e.g., /da/) had .20 probability of occurrence. The onset-to-onset interstimulus interval was 1100 ms. The offset-to-onset ISI was 950 ms. Both speech sounds were presented as standards and deviants in separate runs. Stimulus presentation order within a run was pseudo-randomized, with the provision that there were not more than two successive deviant stimuli and the first stimulus could not be a deviant. The 65 dB ppe SPL intensity was selected because of its similarity to conversational speech levels. The 80 dB ppe SPL intensity was selected because it is a higher intensity and therefore mimics, in part, the effects of amplification. Inclusion of this intensity allows for examination of whether noise-masked stimuli that were inaudible at 65 dB ppe SPL become audible at 80 dB and whether stimuli not discriminable at the lower intensity become discriminable. Additionally, this is the same intensity we previously employed in a study with hearing-impaired infants (Stapells et al., in preparation), and we hoped to explain some of the results of that study.

Maskers

The speech stimuli were presented to the right ear in QUIET, and in conditions where they were mixed with ipsilateral masking noise. The masking noise (Nicolet white noise generator, model NIC-1007a) was fed to a filter (Wavetek, model 852) with both channels set to high pass and

connected in series (96 dB/octave slope). After passing through the filter, the noise was attenuated (Med Associates, model ANL 918) and the output of this attenuator/mixer was fed to another attenuator/mixer where the noise masker was mixed with the stimulus (either the speech sounds for the ERP experiment or the pure tones for the masked behavioral audiograms), and then fed to a passive attenuator and an EAR-3A insert earphone. The level of the broadband noise (BBN) required to fully mask the behavioral perception of the 65 dB ppe SPL speech sounds was determined by increasing the masking level in 10-dB steps until the speech sounds were not audible. The masking level was then decreased by 10 dB and a bracketing approach was initiated using a 1-dB step size. Masked threshold was defined as the level at which the speech sounds were inaudible 50% of the time. The masking noise was then increased 7 dB above this level to ensure adequate masking of the speech sounds. These broadband masking levels ranged from 78.8 to 84.8 dB SPL for the 10 subjects, with a mean level of 81.7 dB SPL. Without changing noise level, the noise was subsequently high-pass filtered using filter settings of 4000, 2000, 1000, 500 and 250 Hz. The same absolute noise intensity was used for both the 65 and 80 dB ppe SPL speech stimuli. The 80 dB ppe SPL stimuli, therefore, were not completely masked and they remained audible, even in broadband noise, but not discriminable under some conditions.

EEG Recordings

Seven EEG channels were recorded from electrodes placed at Fz, Cz, Pz, M1, M2, C3M (midway between C3 and M1), and C4M (midway between C4 and M2), all referenced to an electrode at the tip of the nose (Vaughan and Ritter, 1970). An eighth channel to monitor vertical eye movements and eyeblinks (EOG) was recorded from electrodes on the right supraorbital ridge of the frontal bone and on the zygomatic bone under the right eye. An electrode placed on the neck served as ground. Electrode impedances were maintained below 5000 Ohms, with differences between electrode pairs not exceeding 2000 Ohms. The seven EEG channels were amplified (gain = 10,000), filtered (0.1 to 100 Hz, 6 dB/octave slope), and digitized (568 Hz per channel, 512 points) using a 900-ms analysis time (including a 100-ms pre-stimulus baseline, against which amplitude measures were made). The EOG channel was filtered and digitized as

above, but amplifier gain was set to 5000. ERP waveforms were saved for off-line baseline correction, digital filtering (30 Hz low-pass filter, 12 dB/octave), artifact rejection ($\pm 100 \mu\text{V}$ in any of the EEG/EOG channels), and averaging. ERPs were averaged separately for each stimulus. Two replications of each condition were obtained for each intensity to assess response reliability.

Behavioral Measures

Behavioral pure-tone audiograms obtained in QUIET and in the presence of the noise maskers were obtained for all of the subjects from 250 to 4000 Hz using a Beltone 10D audiometer. Testing was performed in a double walled sound attenuating booth.

Measures of reaction time (RT) and percent correct discrimination were obtained simultaneously with the ERP measures using button-press responses to the deviant stimuli. Measures of median reaction time, and number of hit, false alarm, correct rejection and miss trials were obtained, and criterion-free measures of sensitivity (d') were calculated.

Calibration

The calibrations of the speech sounds, broadband noise, pure-tone stimuli (for the masked and nonmasked audiograms), and EEG amplifiers, were checked daily. The speech sounds were calibrated in dB ppe SPL (relative to a 1000 Hz tone, using the vowel portion of the syllables) and the noise and tones in dB SPL using a Brüel and Kjaer sound level meter (model 2209), Brüel and Kjaer coupler (model 4152) with a 2-cc adaptor (model DB0138). Amplifier channels were calibrated by sending a 50- μV square wave generated by the Grass amplifier through the amplifier channels and into the Neuroscan "SCAN". All channels were within $\pm 2.5 \mu\text{V}$ of 50 μV .

Procedure

The experiment consisted of 65 and 80 dB ppe SPL stimulus intensity conditions which were run on separate days. The sessions took place in a double-walled sound-attenuated booth. Subjects were instructed to fixate on a small dot placed approximately 1.5 meters in front of them at eye level, to minimize eyeblinks, and to press a button as soon as they heard the deviant stimulus. They were advised to place equal weight on the speed and accuracy of their button presses. Subjects were trained on the button-press task using two runs of 100 stimuli in the QUIET

condition. Subjects were required to have at least 90% accuracy over both training runs for inclusion in the study.

Responses to the speech sounds were obtained in QUIET, in broadband noise, and in 250, 500, 1000, 2000, and 4000 Hz high-pass noise. The QUIET condition was always tested first to ensure that a response was present. This was followed by a broadband noise condition to ensure that the masking level was adequate to eliminate responses to the 65 dB ppe SPL stimuli. The remaining conditions were randomized for each subject, and the QUIET condition was repeated at the end of the experiment.

Data Analysis

After offline processing (baseline correction, artifact rejection and digital filtering), the single-trial responses were averaged so that responses to stimuli presented as standards and deviants were grouped separately. On average, across all subjects and all conditions, 90% of the responses to the standard and 90% of the responses to the deviant stimuli remained after artifact rejection. Replications were averaged together for each condition. Difference waveforms for each condition, used to measure N2, were obtained by subtracting averaged responses to the stimuli presented as standards from the averaged responses to the stimuli presented as deviants.

Latency windows to aid in response measurement for data from individual subjects were developed using the data from the grand mean waveforms (10 subjects). The onset of the response windows was developed using the grand mean data from the QUIET conditions minus approximately 10% of the peak duration to accommodate individual subjects whose responses were earlier than the grand mean. Additionally, the noise-masked data from individual subjects were inspected to ensure that the windows were adequate. The offset of response windows was developed using the grand mean responses from the most difficult conditions where responses were present in the grand mean data (250 Hz high-pass conditions for both stimulus intensities and the BBN condition for the 80 dB pe SPL stimulus intensity) as well as inspection of the data from individual subjects. Response windows were 80-200 ms for N1, 200-420 ms for N2 and 285-800 ms for P3. N1 was measured in the waveforms to the stimuli presented as standards at Cz; P3

was measured in the waveforms to the stimuli presented as deviants at Pz; N2 was measured in the difference waveforms at Cz. These measurement locations were chosen because largest amplitudes were seen at these sites in the grand mean waveforms. Measurements were made on the average of the two replicated waveforms for each condition. Amplitude measures were determined at the point of largest amplitude within the response window. Latency measures were taken at the center of the peak within the window. In cases where a wave was multi-peaked, both amplitude and latency measures were taken at the point of largest amplitude within the response window. In cases of double peaks of equal amplitude, amplitude was measured at either peak, and latency was measured at the midpoint of the waveform. For P3, measures were obtained after digital low-pass filtering at 5 Hz (12 dB/oct) in the frequency domain to smooth the waveform (Picton, 1992).

Determination of response presence/absence required the agreement of two judges. The presence of N1 was determined using the waveforms to the stimuli presented as standards. N1 was required to be larger in amplitude at fronto-central electrode sites than at parietal electrode sites. Inversion at the mastoid electrode sites confirmed response presence, but lack of inversion was not used to indicate response absence. The presence of N2 was determined using the difference waveforms. N2 was required to be larger in amplitude at fronto-central electrode sites. When questionable, the waveforms to the stimuli presented as standards and deviants were compared and larger negativity in the waveforms to the deviant stimuli than to the standard stimuli in the N2 latency window was required for N2 presence. The presence of P3 was determined using the waveforms to the stimuli presented as deviants. P3 was required to be larger at Pz than at frontocentral electrode sites. When questionable, the waveforms to the stimuli presented as standards and deviants were compared, and larger positivity in the waveforms to the deviant stimuli than to the standard stimuli in the P3 latency window was required for P3 presence. When judgements were considered questionable using the above rules, the replicability of the waveforms was examined. If the wave was replicable, then it was judged as present. When a wave was judged to be absent, measures for it were given an amplitude of zero μV .

Three-way repeated measures analyses of variance (ANOVA) as a function of speech stimulus, stimulus intensity, and noise condition were carried out on the amplitude and latency data. Main effects and interactions from the ANOVA were considered significant if $p < .01$. Greenhouse-Geisser epsilon correction factors were applied to the degrees of freedom where appropriate (Greenhouse and Geisser, 1959). For latency measures, the repeated measures ANOVAs were performed in a manner to maximize the number of conditions in the analysis. This required that some subjects be eliminated in order to avoid missing data. Conditions were eliminated, however, if fewer than seven subjects remained. Tukey Honestly Significant Difference (HSD) *post-hoc* measures were performed only when significant main effects or interactions were obtained (Tukey, 1953). The *post-hoc* results were considered significant when $p < .10$. This level of significance was selected so that significant main effects and interactions indicated by the ANOVAs (using the more strict $p < .01$ criteria) were likely to be delineated by the *post-hoc* analyses. Pearson product-moment correlation coefficients were calculated between the behavioral measures of discrimination and reaction time and N1, N2 and P3 latency and amplitude. Results of correlational analyses were considered to be significant when $p < .01$.

3D. RESULTS

Masked Audiograms

Behavioral masked and nonmasked pure-tone audiograms are displayed in Figure 2 (see Figure 2). Shown are the mean threshold data in dB SPL for the 10 subjects, and corresponding standard deviations. The masking noise produced moderate threshold elevations at and above the filter cutoff. Across all cutoff frequencies, the high-pass noise increased thresholds by an average of 38 dB at the high-pass cutoff and by 50 dB one octave above the cutoff frequency. Thresholds for frequencies below the cutoff frequency remained essentially unchanged.

Sensitivity (d')

Figure 3 shows the behavioral results calculated from button-press responses to the deviant stimuli that were obtained during the ERP recordings (see Figure 3). The top graph displays d' measures, which reflect the discriminability of the stimuli, as a function of noise condition. Results for the two deviant speech stimuli are collapsed as there was no significant difference in their discriminability [$F(1,9) = 1.82$; $p = .210$]. Results for the two QUIET conditions are averaged in this and all other graphs, as there were no clear and significant differences between the QUIET condition tested at the start of the experiment and the QUIET condition tested at the end of the experiment. Discriminability decreased as the high-pass noise cutoff decreased [$F(7, 30) = 28.96$; $p < .001$]. *Post-hoc* testing indicated that discriminability does not change significantly until the noise cutoff frequency is below 2000 Hz. After this point, discriminability drops off sharply to near-zero levels. The 80 dB ppe SPL stimuli were not discriminated once the high-pass cutoff frequency extended down to 500 Hz and below, even though they were audible. Although across all conditions the d' scores are significantly larger for the 80 dB ppe SPL stimuli than for the 65 dB ppe SPL stimuli [$F(1,9) = 14.40$; $p = .004$], this significant effect is probably the result of the trend for a larger effect of the masking on the responses to the 65 dB compared to the 80 dB speech sounds. This trend, however, was not quite sufficient to result in a significant intensity by condition interaction [$F(7, 23) = 2.77$; $p = .014$]. Further evidence for this lack of difference is that mean d' values in the QUIET conditions are 4.40 for 65 dB and 4.41 for 80 dB.

Reaction Time

The lower portion of Figure 3 shows the reaction time (RT) measures to the deviant stimuli (see Figure 3). For both behavioral and ERP measures of latency, only conditions with at least seven subjects showing responses are plotted. Results were collapsed across speech sounds because there is no significant difference in reaction time between the two deviant speech stimuli [$F(1,6) = 2.07$; $p = .200$]. No significant stimulus intensity effect is present [$F(1,6) = .47$; $p = .520$]. Decreasing the high-pass cutoff frequency resulted in significantly increased RTs [$F(4,12) = 32.38$;

$p < .001$]. The RT results are similar to d' results in that *post-hoc* testing indicates that no significant change in RT occurred until the 1000-Hz high-pass noise condition.

Event-Related Potentials

The grand mean waveforms of all 10 subjects for /ba/, presented at 80 dB ppe SPL in the QUIET condition, are displayed in Figure 4 (see Figure 4). Responses recorded at midline electrode sites Fz, Cz and Pz and in the EOG channel are shown. The difference waveforms were obtained by subtracting the responses to the stimuli presented as standards from the responses to the same stimuli presented as deviants. N1 was measured at Cz in the waveforms to the stimuli presented as standards. It is typically largest at frontocentral electrode sites (Vaughan and Ritter, 1970). N2 was measured at Cz in the difference waveforms (Novak, Ritter, Vaughan and Wiznitzer, 1990), and P3 was measured in the waveforms to the stimuli presented as deviants at Pz (Vaughan and Ritter, 1970). As indicated in Figure 4, these electrode sites are where the responses in this study were largest in the grand mean waveforms. The EOG channel was monitored to reject trials contaminated by eye movements and blinks to ensure that deflections contaminated by eye movements would not be considered responses.

The grand mean waveforms recorded in all the QUIET and masking conditions to the /ba/ and /da/ stimuli at 65 and 80 dB ppe SPL are shown in Figure 5 (see Figure 5). Responses to the standards are displayed for Cz; responses to the deviants are displayed for Pz. There are essentially no differences between the responses to the two speech sounds. In QUIET, and in the 4000 and 2000 Hz high-pass noise conditions, a clear P3 is present in the grand mean waveforms to the deviant stimuli. In contrast, P3 is not present in the broadband noise condition. In the 1000 to 250 Hz high-pass noise conditions, P3 decreases in amplitude and increases in latency until it disappears with further masking into the lower frequencies. Results for P3 for the two intensities are fairly similar. In contrast to P3, N1 shows a different pattern as a function of noise condition and stimulus intensity. In general, as high-pass noise cutoff decreases, N1 amplitude decreases and latency increases. For the 80 dB ppe SPL stimuli, N1 is clearly present in the grand mean waveforms for all noise conditions, including broadband noise. For the 65 dB ppe SPL stimuli, N1

remains present for high-pass noise cutoffs through approximately 500 Hz. As would be expected, N1 to the 65 dB ppe SPL speech sounds is completely masked by the broadband noise.

The grand mean difference waveforms for /ba/ and /da/ presented at 65 and 80 dB ppe SPL are displayed in Figure 6 (see Figure 6). There are no clear differences in the responses to the different stimuli or intensities. N2 is present in the difference waves for the QUIET condition and in the waveforms for the 4000 and 2000 Hz high-pass noise conditions. N2 is not clearly present in the 500 Hz high-pass noise through broadband noise conditions. N2 amplitude decreases with high-pass noise masking, with the greatest change occurring when the cutoff is below 2000 Hz. Latencies first increase at approximately the 2000 Hz high-pass noise condition.

N1

Figure 7 displays the effects of the noise conditions on N1 amplitudes and latencies (see Figure 7). The data in these and all other graphs are collapsed across the /ba/ and /da/ speech stimuli because, in most cases, the effects of noise masking were the same for both stimuli. For N1 to the 80 dB ppe SPL stimuli, amplitudes decrease gradually from -3.99 μ V for the QUIET conditions down to -2.36 μ V for the broadband noise condition. For N1 to the 65 dB ppe SPL stimuli, amplitudes decrease gradually through the 2000-Hz high-pass cutoff frequency and drop off more steeply thereafter. N1 amplitudes in response to the 65 and 80 dB ppe SPL stimuli were similar in the QUIET through approximately 2000-Hz noise conditions. As the high-pass cutoff frequency was further lowered, the noise resulted in a greater decrease in amplitude for the 65 dB stimuli than for the 80 dB ppe SPL stimuli, resulting in a significant intensity x condition interaction [$F(7,21) = 6.41$; $p < .001$]. *Post-hoc* analyses reveal that, for the 65 dB ppe SPL speech sounds, N1 amplitudes for the 250-Hz and BBN conditions are significantly smaller than for the QUIET through 1000-Hz conditions. Additionally, the N1 amplitudes for the 250-Hz and BBN conditions for the 65 dB ppe SPL stimuli are significantly smaller than the QUIET through 250-Hz conditions for the 80 dB ppe SPL stimuli.

Progressively lowering the cutoff frequency of the high-pass noise results in progressively increased N1 latencies [$F(5,16) = 31.50$; $p < .001$]. This effect was gradual for both stimulus intensities. *Post-hoc* analysis indicated that the main effect of noise condition was due to the longer latency of N1 in the 500-Hz high-pass noise condition compared to the QUIET through 1000-Hz high-pass noise conditions. The latency of N1 was longer for the 65 dB ppe SPL speech sounds than for the 80 dB ppe SPL speech sounds [$F(1,8) = 13.72$; $p = .006$], even in the QUIET condition. The specific speech stimulus also affected latency: N1 latencies to /ba/ were longer than to /da/ [$F(1,8) = 36.69$; $p < .001$], even in the QUIET condition (116 versus 110 ms).

N2

The effects of the noise conditions on N2 amplitudes and latencies are displayed in figure 8 (see Figure 8). Progressively lowering the high-pass cutoff frequency resulted in decreased N2 amplitudes [$F(7,13) = 20.18$; $p < .001$]. *Post-hoc* testing indicates that responses in the QUIET conditions have significantly larger amplitudes than the 500 Hz high-pass through BBN conditions. No significant stimulus [$F(1,9) = 2.41$; $p = .155$] or intensity [$F(1,9) = 1.72$; $p = .222$] effects are present. N2 latencies increase as the high-pass noise cutoff frequency decreases [$F(4,15) = 16.77$; $p < .001$]. *Post-hoc* testing reveals longer latencies for the 1000-Hz high-pass conditions than for the QUIET and 4000-Hz high-pass conditions. No significant stimulus [$F(1,7) = 2.98$; $p = .128$] or intensity [$F(1,7) = .85$; $p = .387$] effects are present for N2 latencies.

P3

The effects of noise condition on P3 amplitudes and latencies are displayed in Figure 9 (see Figure 9). Lowering the high-pass noise cutoff below 2000 Hz results in decreased P3 amplitudes. This is reflected statistically in a significant main effect of noise condition on P3 amplitude [$F(7,26) = 49.07$; $p < .001$]. *Post-hoc* testing shows that this effect is due to smaller amplitudes for the 500-Hz high-pass noise through BBN conditions compared to the QUIET through 2000-Hz high-pass noise conditions. P3 amplitudes are larger to the 80 dB ppe SPL stimuli than to the 65 dB ppe SPL stimuli [$F(1,9) = 14.87$; $p < .001$], though there was a trend toward a greater effect of

the noise conditions on the lower intensity stimuli when the noise extended below 1000 Hz. This intensity by condition interaction, however, did not reach significance [$F(7,27) = 2.27$; $p = .040$].

High-pass noise cutoff frequency also affects P3 latencies [$F(4,18) = 45.04$; $p < .001$]. *Post-hoc* testing reveals that this is due to longer latencies in the 1000-Hz high-pass noise condition than for the QUIET through 2000-Hz high-pass noise conditions. No stimulus [$F(1,8) = 1.59$; $p = .243$] or intensity [$F(1,8) = .02$; $p = .882$] effects are significant.

Responses associated with the subjects' correct discriminations ("hits") were also analyzed. The overall pattern of these "hit-P3" results is similar to those for the "overall-P3" for latencies and amplitudes (see Figure 9), except that the amplitudes of the P3 responses associated with hits are larger than for the overall-P3 responses [$F(1,9) = 14.87$; $p = .004$]. There were no interactions involving "hit-P3" and "overall-P3".

The relationships between behavioral measures of discrimination and ERP measures were investigated using Pearson product-moment correlations (see Table 1). There is a progression in the correlations between N1, N2, and P3 amplitudes and behavioral d' , such that P3 has a strong relationship to d' , N2 has a moderate relationship, and N1 shows the weakest relationship. The effect of noise condition on d' was similar to that for N2 and particularly P3, with d' scores dropping as the high-pass noise cutoff lowers, most notably below the 2000 Hz cutoff. N2 and P3 amplitudes showed similar changes. In contrast to the correlations with d' , N1, N2 and P3 amplitudes are weakly correlated to behavioral reaction time measures. RT increases gradually in the QUIET through 2000 Hz high-pass conditions and more rapidly as the high-pass noise extends into lower frequencies. This is clearly different from the gradual decrease in amplitude that N1 shows as the high-pass noise cutoff frequency is lowered.

There is a progression in the correlations between N1, N2 and P3 latencies and behavioral reaction time measures such that P3 latency has a moderate relationship, N2 latency has a moderate though slightly weaker relationship, whereas N1 latency shows no significant ($p > .01$) relationship to behavioral reaction times. N1 latency increased only slowly as the high-pass noise

cutoff was lowered. N2 and P3 latencies increased rapidly as the noise cutoff was lowered below 2000 Hz. The correlations between ERP latencies and d' are significant, with N1 and N2 latencies showing a moderate relationship to d' , and P3 latencies showing a stronger relationship (Table 1).

6E. DISCUSSION

The high-pass noise maskers resulted in decreased audibility in specific spectral regions. The resulting audiograms are similar to those seen with steep high-frequency hearing losses. As the noise cutoff frequency was lowered, the portion of the audiogram showing decreased audibility extended from encompassing only the high-frequency regions (in the 4000 and 2000 Hz high-pass conditions) to encompassing both high and mid frequencies (in the 500 and 1000 Hz high-pass conditions) and, in the broadband noise conditions, high, mid and low frequencies. This decreased audibility results in decreased ERP amplitudes and increased ERP latencies. Additionally, the threshold elevations produced by the high-pass noise masking resulted in lower behavioral d' values and increased reaction times. For the stimuli used in this study (/ba/, /da/), the effects of the high-pass noise masking are noteworthy when 1000 to 2000 Hz spectral regions are masked. This is the frequency region where the primary acoustic cues differentiating /da/ from /ba/ occur. As lower frequency regions were masked, ERP amplitudes decreased and latencies increased even further. Behavioral measures indicated the subjects' inability to discriminate the stimuli when these lower frequency regions were masked.

Behavioral Measures

The moderate threshold elevations induced by high-pass noise masking result in decreased ability to behaviorally discriminate the speech sounds /ba/ and /da/. This is reflected in the decreased d' values and increased reaction times when the noise cutoff frequency is lowered below 2000 Hz and the frequency regions containing the second and third formant transitions for the speech sounds are masked. At least for the speech contrast used in this study, the most important frequency region for discrimination was approximately 1000 Hz. The addition of spectral information above 2000 Hz had little effect on discrimination performance.

To our knowledge, the effects of high-pass noise maskers on reaction times, which indicate temporal characteristics of discrimination, have not been investigated previously. Reaction times may provide a metric of processing difficulty or ease of listening (e.g., Downs, 1982; Downs and Crum, 1978). In the present study, reaction time changes occurred when the noise cutoff frequency was lowered below 2000 Hz. This finding suggests, therefore, that the listening task was more difficult when the spectral regions containing the second formant were masked.

Previous studies have demonstrated that reaction times to speech sounds are increased when speech is presented in broadband noise, speech weighted noise, or in multi-talker babble (e.g., Downs and Crum, 1978; Gatehouse and Gordon, 1990; Hecker, Stevens and Williams, 1966). The increase in reaction times seen with high-pass noise masking is consistent with these findings, though the present study had an additional frequency-specific effect. In contrast to studies showing that reaction time may be a more sensitive measure of processing difficulty than percent correct (Gatehouse and Gordon, 1990; Hecker, Stevens and Williams, 1966; Stevenson and Martin, 1977; Whiting, Martin and Stapells, in preparation), the present study shows that reaction times and recognition scores (as measured by d') for consonant-vowel syllables were similarly affected by the high-pass noise conditions. The previous studies, however, did not use high-pass noise masking. The results of the present study also differ with results of studies which indicate reaction times decrease when speech intensity is increased or when speech is amplified using a hearing aid (e.g., Downs, 1982; Wright, Spenner and Martin, 1981). The lack of an effect of intensity on RT in this study may be due to a ceiling effect resulting from our use of relatively high stimulus intensities (65 and 80 dB ppe SPL).

Speech recognition performance is often examined in normal listeners using noise masking (e.g., Bell, Dirks and Carterette, 1989; Fabry and Van Tasell, 1986; Humes, Dirks, Bell and Kinkaid, 1987) or filtering (e.g., Bell, Dirks and Carterette, 1989; Dubno, Dirks and Ellison, 1989; Fabry and Van Tasell, 1986; French and Steinberg, 1947; Kryter, 1960; Miller and Nicely, 1955; Owens, Benedict and Schubert, 1972; Pollack, 1948; Sher and Owens, 1974; Walden, Schwartz, Montgomery and Prosek, 1981; Wang, Reed and Bilger, 1978) of stimuli to control for audibility in

specific spectral regions. The majority of these studies differ in design from the present study. For example, most used open-set recognition designs and examined performance on multiple phonemes. However, there are other reports directly related to those of the present study. For example, the effect of low-pass filtering of stimuli on the recognition of /b/ and /d/ can be extracted from the tables presented by Miller and Nicely (1955). At a signal-to-noise ratio of +12 dB, recognition performance decreased gradually as high frequencies were removed by low-pass filtering. Compared to the present study, however, their subjects' performance was superior in conditions where frequencies above 1200 Hz were removed. The differences in the results of that study and the present study may be due to the use of low-pass filtering of stimuli instead of high-pass noise masking, to different filter slopes, or to inclusion of other consonant-vowel stimuli. Miller and Nicely (1955) used a rejection rate of 24 dB/octave whereas in the present study the filter slope was 96 dB/octave. Dubno, Dirks and Ellison (1989) used a filter with a slope of more than 100 dB/octave, and the recognition data for their subjects are more in line with those of the present study. When performance for /b/ and /d/ at 73 dB SPL are averaged and examined as a function of low-pass filtering of the speech stimuli (see their Figure 2), their subjects' recognition performance dropped significantly when frequencies above 1500 Hz were removed. This is consistent with the findings of the present study showing d' scores dropping when audibility above 1000 Hz is decreased by noise masking (Figure 3).

In the present study, subjects reported that they perceived the stimuli as /ba/ and /da/ until the noise masking included approximately the 1000-Hz region. At this point, the perception of /da/ tended to move toward /ja/. This may be due to partial masking of the second formant transition which may have interfered with the perception of the duration and frequency of the second formant transition. As the masking cutoff frequency was further lowered, the subjects were unable to discriminate the stimuli, and, if the stimuli were audible, tended to report hearing only /a/ for both /da/ and /ba/.

ERP Measures

Decreased audibility of the speech sounds produced by high-pass noise masking results in increased latencies and decreased amplitudes of the ERP peaks. No studies examining the effect of high-pass noise masking on cortical N1, N2 and P3 ERPs to auditory stimuli have previously been published. One earlier study (Polich, Howard and Starr, 1985) examined the effects of 60 dB nHL white noise masking on P3 latency during an auditory frequency discrimination task. Results showed that the white noise increased P3 latencies by approximately 10 ms (Polich, Howard and Starr, 1985). In the present study, the use of 81.7 dB SPL (on average) broadband noise essentially eliminated P3 responses to the speech sounds. However, in noise masking conditions where responses were present (4000 Hz through 1000 Hz high-pass noise), the noise masking resulted in latency increases of 9 ms for N1, 64 ms for N2, and 162 ms for P3 from the QUIET condition. Thus, the masking noise had a differential effect on the N1, N2 and P3 waves. The later the wave, the greater the effect of high-pass noise masking on latency. Studies of the effects of visual masking on cortical ERPs to visual stimuli indicate that increased latencies and decreased amplitudes occur when the visual stimuli are degraded (e.g., Magliero, Bashore, Coles and Donchin, 1984; Ritter, Simson, Vaughan and Macht, 1982). The increased latencies and decreased amplitudes seen in those studies in the presence of visual masking are consistent with the present study and the degree of change seen with visual "masking" is more in line with the findings of the present study than are the small latency increases with white noise masking reported by Polich and colleagues (Polich et al., 1985). The present study adds a frequency-specific effect, particularly in the 1000 to 2000-Hz region, related to the specific speech contrasts. The decreases in amplitudes and increases in latencies resulting from noise masking probably reflect increased task/discrimination difficulty (Bachs, 1987). The high-pass noise makes the determination of whether a particular stimulus is deviant more difficult, resulting in increased latencies and decreased amplitudes. These changes likely reflect increased processing time, increased response variability, and generally less-effective cortical processing.

One of the more interesting findings of the present study is that the threshold elevations produced by the high-pass noise masking have differential effects on N1 *versus* N2 and P3 peaks, at least for ERPs to speech sounds. N2 and P3 show amplitude and latency changes beginning beyond a noise cutoff frequency of 2000 Hz. The frequency region where changes first occur corresponds to the spectral region containing the second formant transition. Unlike N2 and P3, N1 shows a systematic change across noise condition. As the cutoff frequency of the high-pass noise was lowered, N1 amplitudes decreased and latencies increased. The latency increases resulting from the high-pass noise masking are thus greater for the longer latency ERP peaks. In other words, across both stimuli, intensities and all conditions, the high-pass noise masking caused a larger increase in latency for P3 than for N2, and the smallest increase was seen for N1. The same pattern was seen for amplitudes. For example, with data collapsed across stimulus and intensity, P3 amplitude decreased by 4.54 μV when the high-pass noise cutoff was lowered from 2000 Hz to 1000 Hz, N2 amplitude decreased by 2.61 μV , and N1 amplitude decreased by 0.26 μV . Thus, progressively higher-level processing of these stimuli, as indicated by these ERPs, is increasingly disrupted.

N1 latency was longer for /ba/ than for /da/, even in the QUIET conditions (116 *versus* 110 ms). Although statistically significant, this finding was unexpected because the stimuli were equal in intensity, time of onset, and duration. Maiste (1989), using the same stimuli, also reported slightly longer N1 latencies for /ba/ than for /da/ (121 *versus* 118 ms). This may be due to travelling wave delays at the cochlear level for /ba/ relative to /da/ that persist at the cortical level (Békésy, 1960; Hind, 1953). That is, these delays could be due the presence of the lower frequency onset of the F2 transition for /ba/ compared to /da/ (see Figure 1). Another possibility may be a different cortical representation of the two speech sounds due, in part, to their differing frequency composition (e.g., Mendelson and Cynader, 1985; Phillips and Irvine, 1981; Ponton, Don, Waring, Eggermont and Masuda, 1993; Sams and Näätänen, 1991; Steinschneider, Arezzo and Vaughan, 1990). Stimulus intensity affected some, but not all of the ERPs. N1 amplitudes were slightly larger and latencies were significantly shorter in response to the 80 dB ppe SPL stimuli than to the 65 dB ppe

SPL stimuli. This is consistent with studies showing that N1 increases in amplitude and decreases in latency with increases in intensity (e.g., Adler and Adler, 1989; Arlinger, 1976; Davis and Zerlin, 1966; Keidel and Spreng, 1965). N2 showed no effect of stimulus intensity (65 versus 80 dB). Overall-P3 amplitude and hit-P3 amplitude were larger for the 80 dB stimuli than for the 65 dB stimuli, even in the QUIET condition. There was a trend ($.01 < p < .05$) for the effect of intensity to be larger when the high-pass noise extended below 1000 Hz. Behavioral measures, however, did not show differences between responses to the 65 versus 80 dB stimuli in QUIET.

Relationship between behavioral and ERP measures of discrimination

Behavioral measures of sensitivity (d') were correlated both to ERP amplitudes and to ERP latencies. There was a progression in the relationship of d' to ERP amplitudes such that there was a weak relationship with N1 amplitudes, a moderate relationship with N2 amplitudes and a strong relationship with P3 amplitudes. The d' measure was also strongly, though negatively, correlated with N1, N2 and P3 latencies. Behavioral reaction time measures, however, correlated poorly with ERP amplitudes. There was a progression in the relationship of RT with ERP latencies. The correlation between reaction time and ERP latencies was weak for N1, moderate for N2, and strongest for P3.

The presence of N1 appears to reflect only the presence of audible stimulus energy because it was present even when behavioral measures indicated the subjects' inability to discriminate the speech stimuli. Thus, N1 does not provide information on the discrimination of speech stimuli. For example, N1 was present in the broadband masking condition for the 80 dB ppe SPL stimulus intensity; P3 however, was not present in this condition for most subjects and behavioral measures suggested inability to discriminate the speech sounds. In contrast to N1, N2 and P3 are highly correlated with behavioral measures of discrimination, and thus reflect conscious discrimination of the speech sounds. It should be noted that N2 in an attend condition comprises both N2b and the mismatch negativity. Therefore, N2 changes may reflect contributions from the mismatch negativity, an automatic discriminative response (for review, see Näätänen, 1990), as well as from N2b.

As discussed above, the relationship between behavioral indices of discrimination and ERP waves N2 and P3 is relatively strong. As d' decreases, amplitudes decrease. Additionally, as reaction time increases, latencies increase. Specifically, when behavioral performance was good (e.g., QUIET through 2000 Hz conditions), N2 and P3 amplitudes were large and latencies were relatively short. When behavioral performance was poor (e.g., 500 Hz through BBN conditions), N2 and P3 amplitudes were low, and if present, latencies were long.

Because of the strong relationship between behavioral and N2 and P3 electrophysiological measures of discrimination, P3 and perhaps N2 might be used as measures of auditory discrimination in patients with hearing loss. P3 recordings typically require subject participation such as button-press responses to deviant stimuli. Behavioral measures of percent correct discrimination and reaction time are therefore available. A major advantage of ERP recordings over behavioral indices alone is that ERPs provide measures of the sequence, timing and strength of different levels of auditory processing.

Implications

Decreased audibility in specific spectral regions resulted in longer ERP latencies and behavioral reaction times and smaller ERP amplitudes and behavioral d' scores, at least for /ba/ and /da/ stimuli. This suggests that decreased audibility resulting from the masking noise altered brain processes associated with the processing of speech sounds. The time required to process the speech sounds was lengthened, and the amplitudes of the responses to the speech sounds were reduced. Moreover, N1, N2 and P3 were differentially affected by the maskers. These waves permit evaluation of processing within different levels of the auditory system. The increase in latency (ms/octave) and decrease in amplitude (μ V/octave) resulting from the noise maskers are smallest for N1, larger for N2, and largest for P3. Further studies might determine how stimulus evaluation is altered with peripheral compared to central auditory pathologies.

Although the use of masking in normal listeners is a reasonable way to examine the effects of decreased audibility in a controlled manner (e.g., Humes, Dirks, Bell and Kincaid, 1987), decreased audibility resulting from masking noise is not equivalent to sensorineural hearing loss, as

listeners with sensorineural hearing loss have additional problems beyond raised thresholds in specific spectral regions (e.g., Fabry and Van Tasell, 1986; Festen and Plomp, 1983; Scharf, 1978; Thibodeau, 1991). Studies of individuals with sensorineural hearing losses are needed to examine whether the ERP changes seen in this study are also present in hearing-impaired listeners. The ERP changes seen in this study suggest that stimulus evaluation time is increased when audibility is reduced. This slowing could conceivably result in speech perception difficulties, and may provide a partial explanation of the general belief in aural rehabilitation that slowing the rate of speech helps hearing-impaired listeners to better understand a message. Further studies using hearing-impaired listeners may validate this hypothesis.

The 80 dB ppe SPL stimuli were audible in all of the high-pass noise masking conditions, but not discriminable for all conditions. The results obtained with these stimuli may have implications regarding the effects of amplification for individuals with hearing loss. The discriminability (d') of /ba/ versus /da/ was significantly larger at 80 dB compared to 65 dB in the presence of masking, particularly when the masking noise extended into low frequencies. A similar pattern was seen for N1 and P3 amplitudes and N1 latencies. Specifically, amplitudes were larger and latencies were shorter to the 80 dB ppe SPL stimuli compared to the 65 dB ppe SPL stimuli, especially when the noise masking extended into low frequencies. Thus, increasing speech sound discriminability through use of amplification results in stronger and faster brain processing, as indicated by ERP amplitudes (N1, P3) and latencies (N1).

The ERP amplitude and latency changes seen with decreased audibility should be considered when studying populations where hearing impairment is likely, such as the aged. Depending on the degree and configuration of hearing loss, hearing-impaired populations may have responses to speech sounds that are smaller and/or later than those seen in normal listeners. It may be necessary to use more sweeps in order to improve the signal-to-noise ratio of the recordings, and longer sweep times and larger display gains in order to detect responses.

The presence of ERPs provides evidence of brain responsivity to (N1, N2 and P3) and discrimination of (N2, P3) speech sounds. It might, therefore, be beneficial to use them with populations where behavioral measures of speech detection and discrimination are difficult to obtain, such as infants. Unfortunately, it is difficult to record P3 in infants and other patients who are difficult-to-test. Similar work using high-pass noise masking is underway in our laboratory on the mismatch negativity (for review, see Näätänen, 1990), an automatic discriminative response which has been recorded in infants (Alho, Sainio, Sajaniemi, Reinikainen and Näätänen, 1990). Unlike P3, the presence of the MMN does not require active participation/attention by the listener and may therefore permit evaluation of auditory processing in normal or impaired infant populations.

3F. ACKNOWLEDGEMENTS

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Table 1. Results of correlational analyses between behavioral [sensitivity (d') and reaction time (RT)] and ERP measures [N1, N2 and P3]. Shown are Pearson product-moment correlation coefficients.

		AMPLITUDE			LATENCY		
		N1	N2	P3	N1	N2	P3
d'	r	.50*	.63*	.78*	-.67*	-.55*	-.78*
	N	320	320	320	269	221	240
RT	r	-.34*	-.32*	-.25*	.22	.41*	.56*
	N	205	205	205	202	197	203

*p < .01

FIGURE CAPTIONS

Figure 1. The acoustic waveforms, wideband spectrograms, and a schematic of the spectrograms showing the frequencies of the first three formants and the formant transitions (obtained from LPC formant analyses) are displayed for the /ba/ and /da/ stimuli.

Figure 2. Mean (top) and standard deviation (bottom) behavioral pure-tone masked and nonmasked audiograms across the 10 subjects are displayed in dB SPL as a function of pure-tone frequency. Audiograms are shown for the QUIET (nonmasked) condition, 4000 Hz through 250 Hz high-pass noise masked conditions, and the broadband noise (BBN) masked condition.

Figure 3. The top graph displays d' measures of the discriminability of the stimuli as a function of noise masking condition, along with corresponding standard deviations. The lower graph displays reaction times as a function of noise masking condition, along with corresponding standard deviations. Circles indicate the data for the 65 dB ppe SPL speech stimuli, and triangles indicate the data for the 80 dB ppe SPL stimuli. Data are pooled across /ba/ and /da/.

Figure 4. The grand mean waveforms to /ba/, presented at 80 dB ppe SPL in the QUIET condition are displayed at Fz, Cz, Pz and in the EOG channel. The top row of waveforms are the responses to the stimuli presented as standards (thick line) and as deviants (thin line). The bottom row of waveforms are the difference responses calculated by subtracting the responses to stimuli presented as standards from the responses to stimuli presented as deviants. N1, N2 and P3 waves are labelled. In this and subsequent figures, positivity is represented as an upward deflection.

Figure 5. The grand mean waveforms recorded in all of the noise conditions to the /ba/ and /da/ stimuli at 65 and 80 dB ppe SPL are displayed. QUIET-S indicates responses in the QUIET condition at the start of the experiment and QUIET-E denotes responses in the QUIET condition at the end of the experiment. The high-pass noise condition are denoted by the letters HP followed by the noise cutoff frequency. Responses to stimuli presented as standards are displayed for Cz (thick line) and responses to stimuli presented as deviants are displayed for Pz (thin line). The arrow indicates stimulus onset.

Figure 6. The grand mean difference waveforms for /ba/ and /da/ presented at 65 and 80 dB ppe SPL are displayed for Cz. QUIET-S denotes responses in the QUIET condition recorded at the start of the experiment and QUIET-E indicates responses in the QUIET condition recorded at the end of the experiment. The high-pass noise conditions are indicated by the letters HP followed by the noise cutoff frequency. The arrow indicates stimulus onset.

Figure 7. The top graph displays the effects of the high-pass noise masking on mean N1 amplitudes. The lower graph displays the effects of the high-pass noise masking on mean N1 latencies. Corresponding standard deviations are also displayed. Circles indicate results for the 65 dB peSPL speech sounds and triangles indicate results for the 80 dB peSPL speech sounds.

Figure 8. The top graph displays the effects of the high-pass noise masking on mean N2 amplitudes. The lower graph displays the effects of the high-pass noise masking on mean N2 latencies. Corresponding standard deviations are also displayed. Circles indicate results for the 65 dB peSPL speech sounds and triangles indicate results for the 80 dB peSPL speech sounds.

Figure 9. The top graph displays the effects of the high-pass noise masking on mean P3 amplitudes. The lower graph displays the effects of the high-pass noise masking on mean P3 latencies. Corresponding standard deviations are also displayed. Circles indicate results for the 65 dB peSPL speech sounds and triangles indicate results for the 80 dB peSPL speech sounds for overall-P3; the dotted lines indicate results for the 65 dB peSPL speech sounds and the dashed lines indicate results for the 80 dB peSPL speech sounds for P3 associated with correct button-press responses (hit-P3).

Figure 1

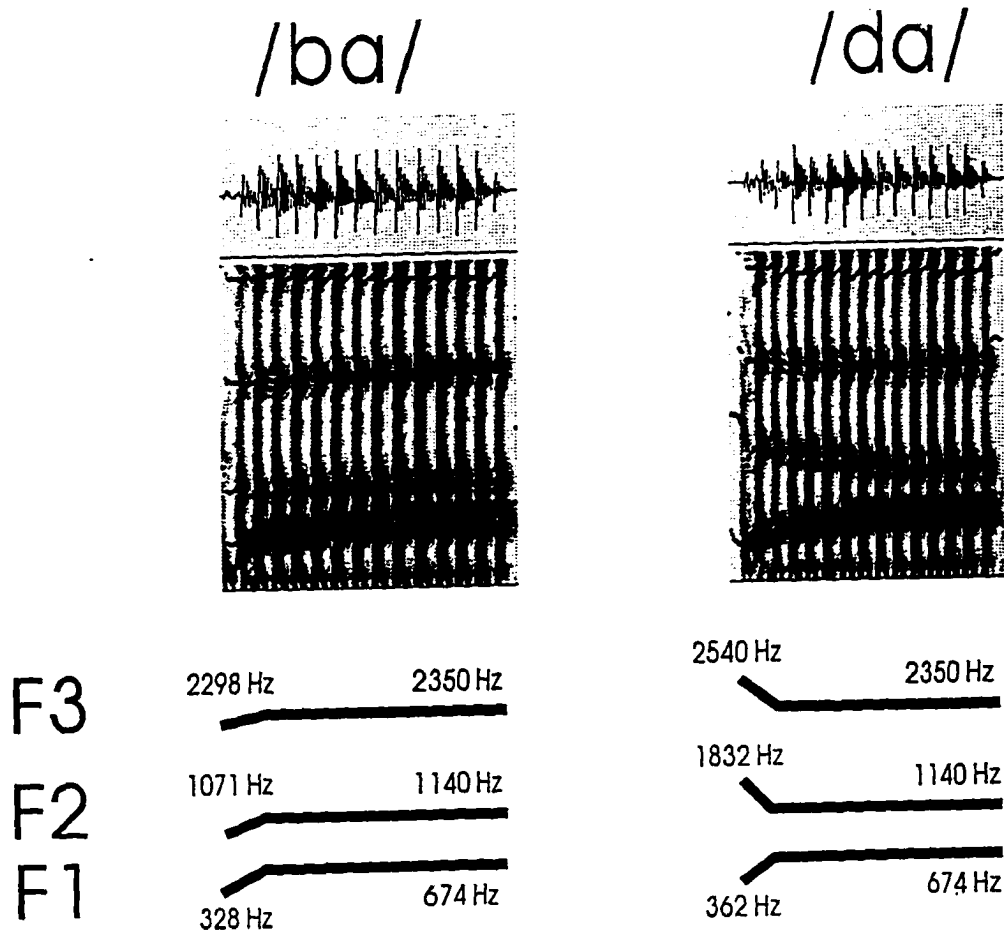


Figure 2

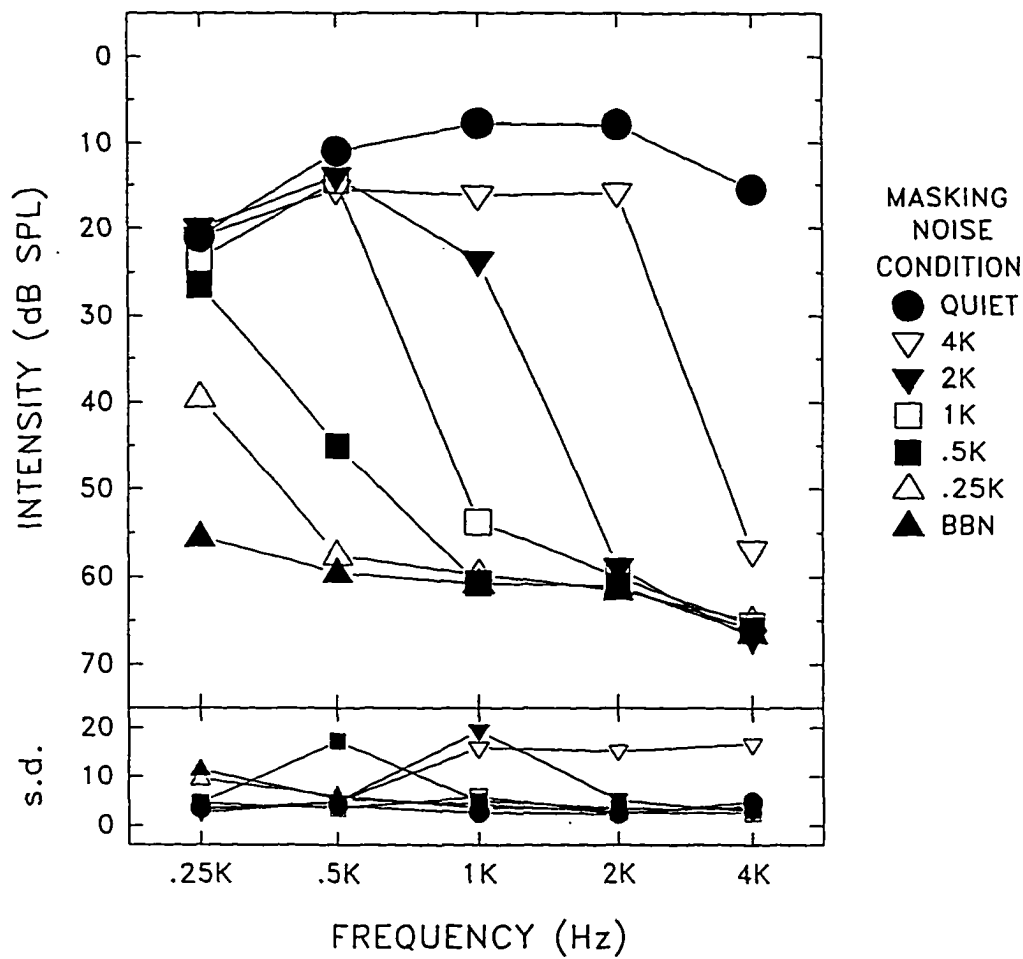


Figure 3

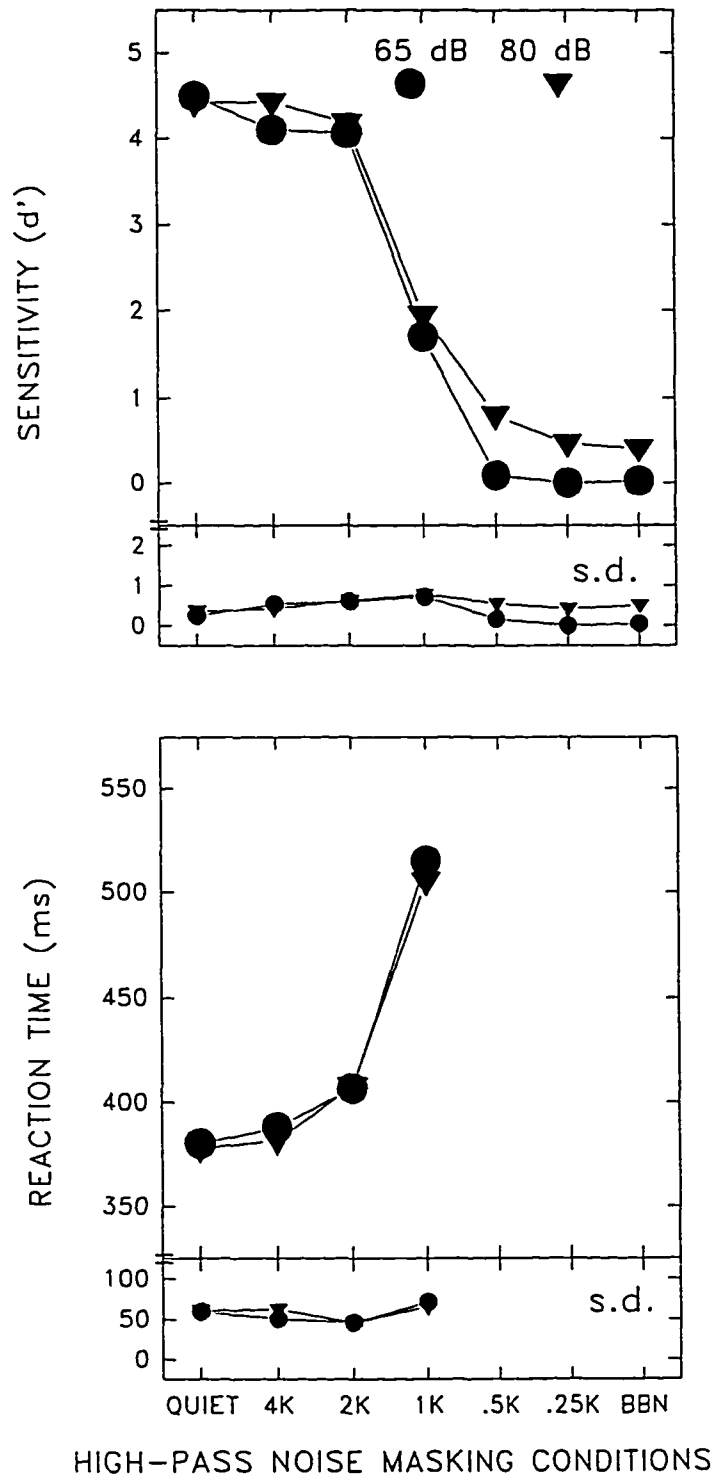


Figure 4

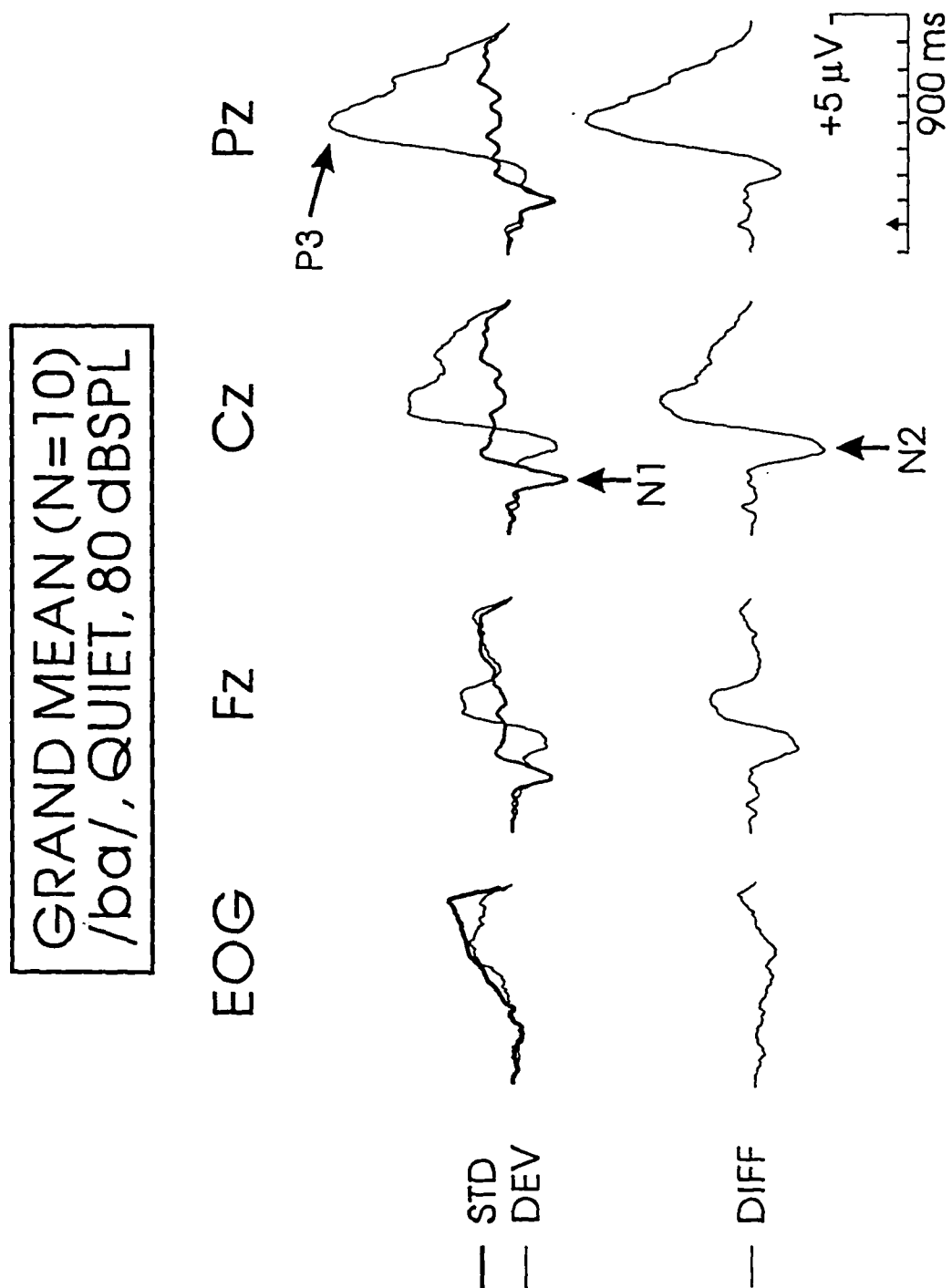


Figure 5

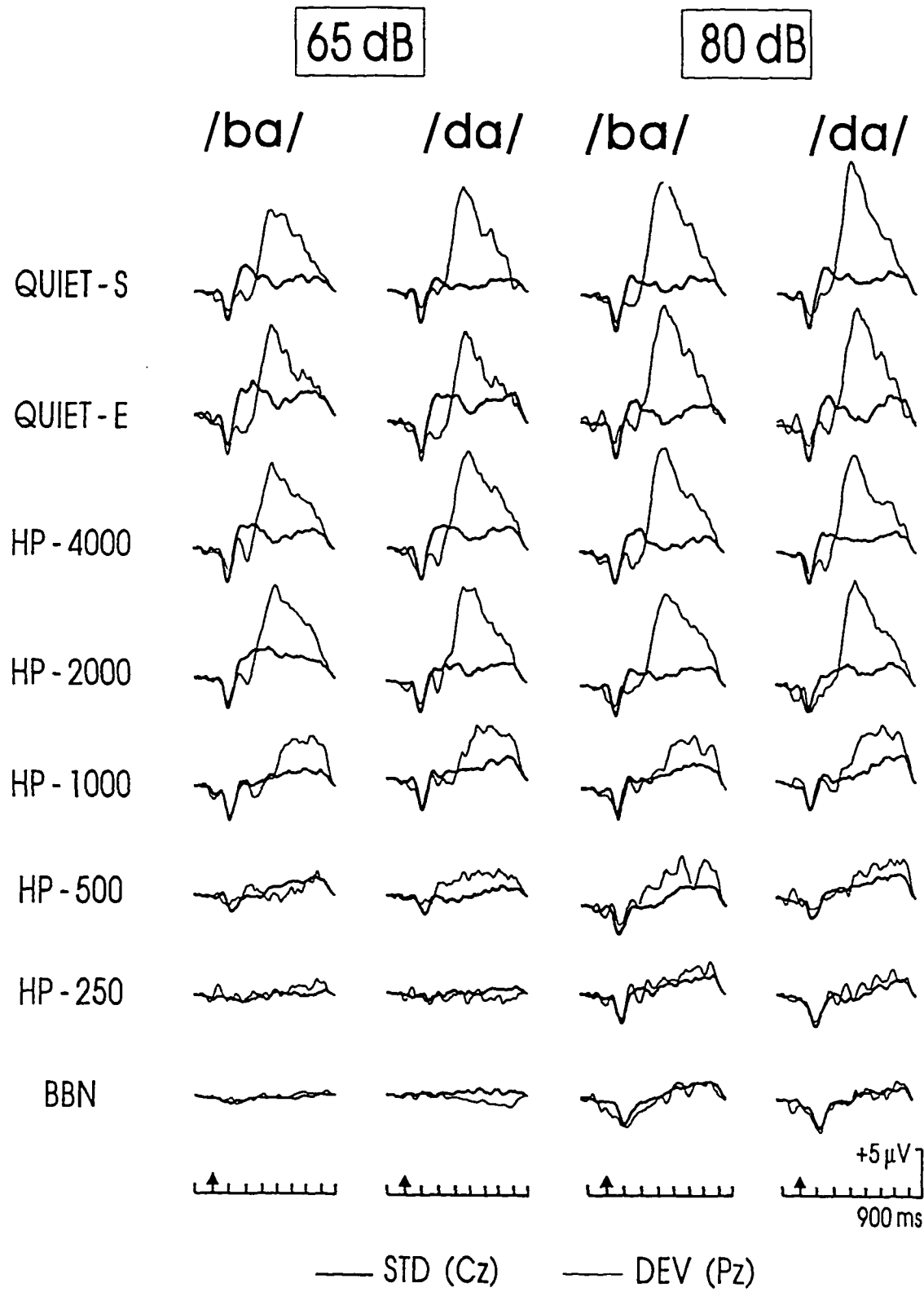


Figure 7

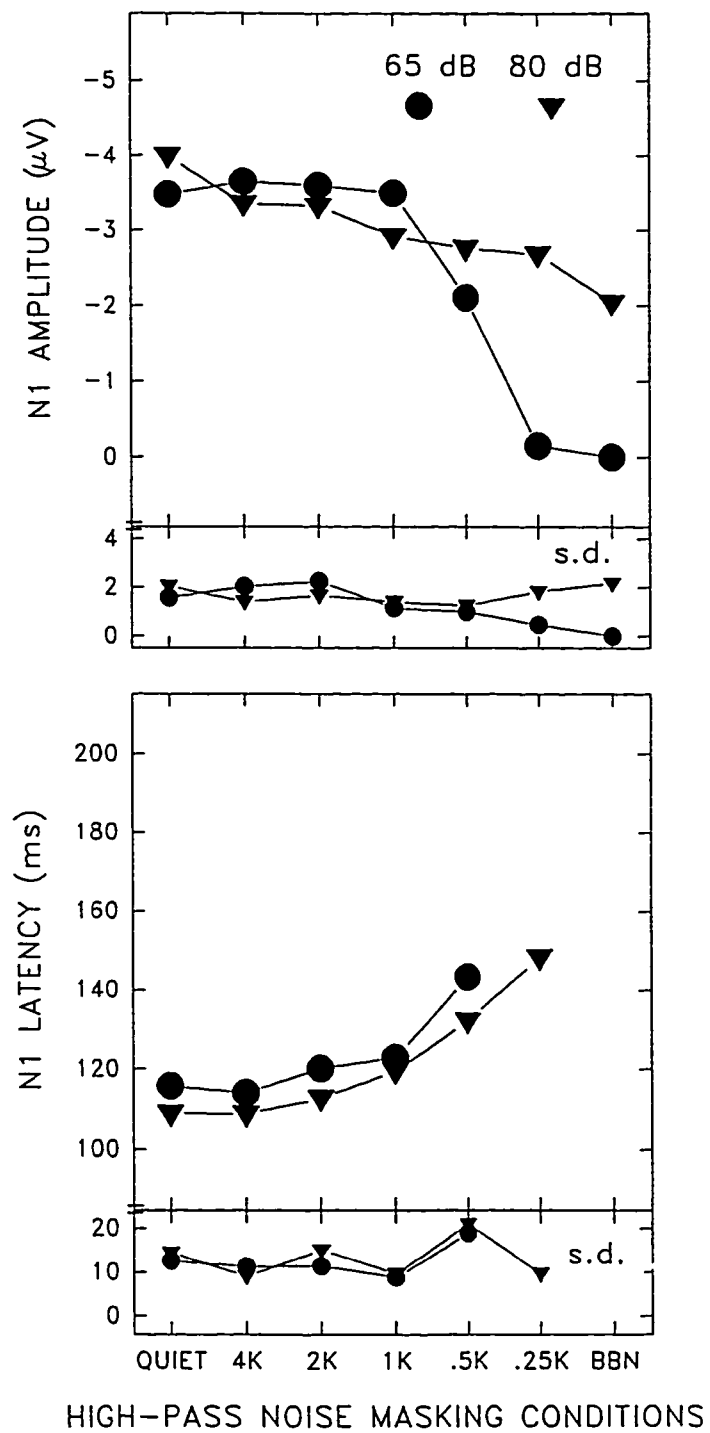


Figure 8

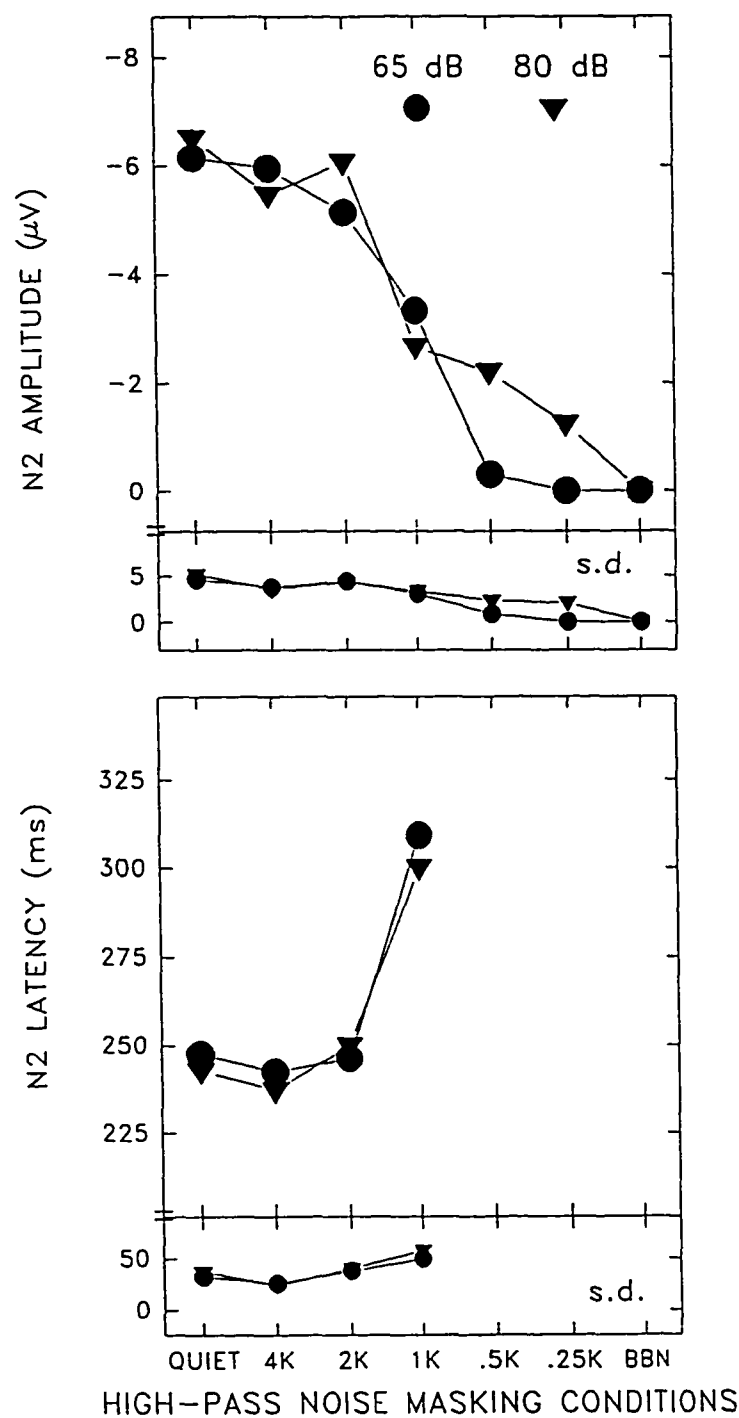
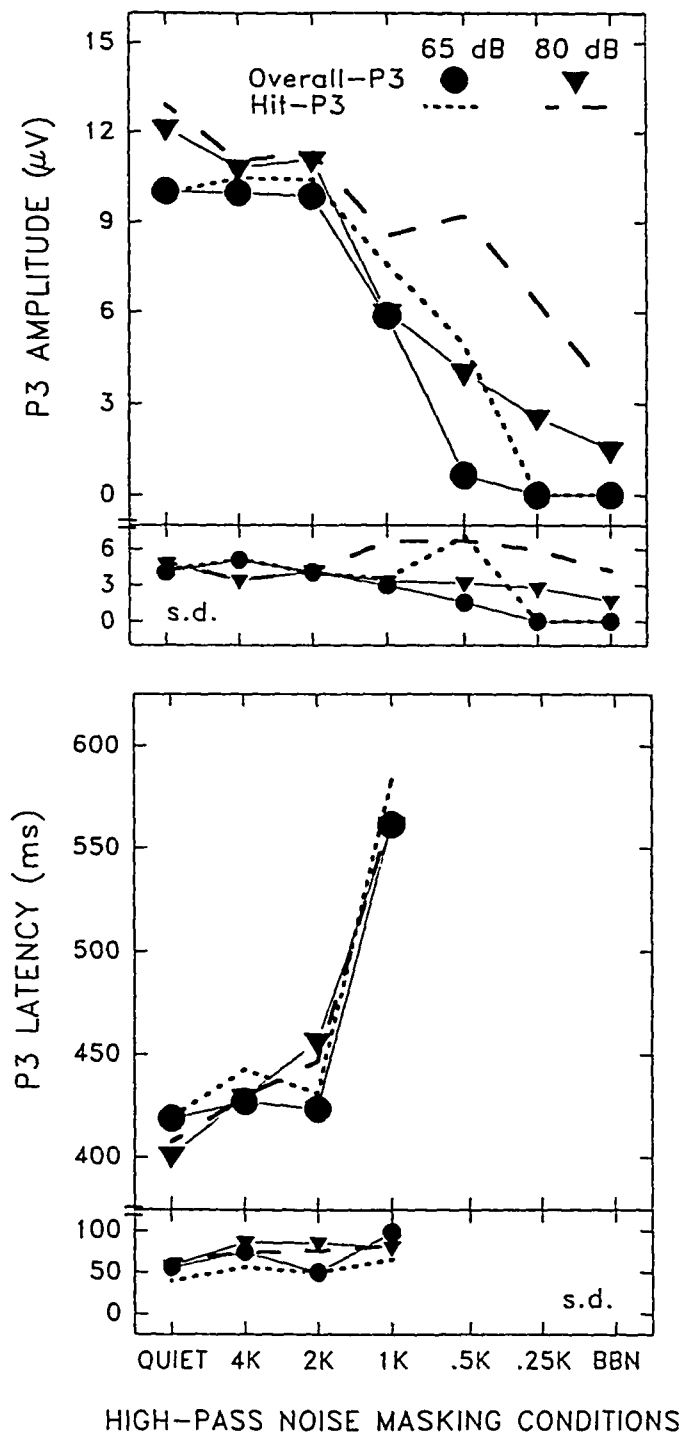


Figure 9



Chapter 4

**The effects of decreased audibility produced by high-pass noise masking
on N1 and the mismatch negativity to speech sounds /ba/ and /da/.**

4A. Abstract

This study investigated the effects of decreased audibility produced by high-pass noise masking on the cortical event-related potentials (ERPs) N1 and mismatch negativity (MMN) to the speech sounds /ba/ and /da/, presented at 65 dB peak-to-peak equivalent SPL. ERPs were recorded while subjects (N=11 normal listeners) ignored the stimuli and read a book. Broadband masking noise was simultaneously presented at an intensity sufficient to mask the response to the speech sounds, and subsequently high-pass filtered. The conditions were: QUIET (no noise), high-pass cutoff frequencies of 4000, 2000, 1000, 500 and 250 Hz, and broadband noise. Derived responses were calculated to obtain ERPs representing octave-wide bands with center frequencies of 2000, 1000, 500, 250 and <250 Hz. Behavioral measures of discrimination of the speech sounds (d' and reaction time) were recorded separately from the ERPs for each subject and condition.

As the cutoff frequency of the high-pass masker was lowered, ERP latencies increased and amplitudes decreased. The cutoff frequency where changes first occurred differed for N1 compared to MMN. N1 showed small systematic changes across frequency beginning with the 4000-Hz high-pass noise. MMN and behavioral measures showed large changes that occurred at approximately 1000 Hz. Derived response N1 amplitudes contained contributions from a broad region of the basilar membrane, but were maximal at a center frequency of 250 Hz. Derived MMN amplitudes were largest at center frequencies of 500 - 1000 Hz for /ba/, and at 1000 Hz for /da/.

These results indicate that decreased audibility, resulting from the masking, affects N1 and the MMN in a differential manner. N1 reflects the presence of audible stimulus energy, being present in all conditions where stimuli were audible, whether or not they were discriminable. The MMN is present only for those conditions where stimuli were discriminable. These cortical ERP in high-pass noise studies provide insight into the changes in brain processes and behavioral performance which occur when audibility is reduced, as in hearing loss.

4B. Introduction

Event-related potentials (ERPs) provide a means of measuring the timing and sequencing of speech sound processing. The cortical auditory ERP N1 is an obligatory potential that is elicited approximately 100 ms after acoustic stimulus onset. The N1 is preceded by the positive obligatory P1 wave, and is followed by the obligatory positive wave, P2, occurring approximately 200 ms after stimulus onset. N1 varies with physical characteristics of the stimulus, with stimulus rate, and is affected by subject state (for review, see Näätänen and Picton, 1987).

In an oddball paradigm (e.g., /ba, ba, ba, ba, ba, da, ba/, etc.), infrequently occurring deviant stimuli (e.g., /da/) are embedded within a series of frequently occurring standard stimuli (e.g., /ba/). The N1 is elicited by both standard and deviant stimuli (e.g., Näätänen, 1990). There is an increased negativity in response to the deviant sound that often begins during the N1 and usually lasts longer than N1. This negativity may appear as an enlarged N1, a second negative peak, or as an attenuation of the P2 wave (Picton, 1990). This negativity, called the mismatch negativity (MMN), is best seen by subtracting the response to stimuli presented as standards from the response to stimuli presented as deviants. The MMN is an automatic discriminative response that does not require active participation or attention by subjects (e.g., Näätänen, 1990). The MMN is sensitive to changes in the acoustic properties of a stimulus, and may be elicited by changes in stimulus frequency (Sams, Paavilainen, Alho, and Näätänen, 1985), intensity (Näätänen, Paavilainen, Alho, Reinikainen, and Sams, 1987), duration and timing (Näätänen, Paavilainen and Reinikainen, 1989), or spatial location (Paavilainen, Karlsson, Reinikainen, and Näätänen, 1989). MMN amplitude increases and latency decreases as the physical difference between the standard and deviant stimuli increases (Sams, Paavilainen, Alho and Näätänen, 1985). Response amplitude is maximal at fronto-central scalp locations, though it may also be large at temporal scalp locations (e.g., Alho, 1995). The MMN appears to be specific to the auditory modality (Nyman, Alho, Laurinen, Paavilainen, Radil, Reinikainen, Sams and Näätänen, 1990), though it has been shown

to be modulated by visual input (Sams, Aulanko, Hamalainen, Hari, Lounasmaa, Lu and Simola, 1991).

Both the obligatory N1 (e.g., Dorman, 1974; Friedman, Simson, Ritter and Rapin, 1975; Wood, 1975; Wood, Goff and Day, 1971; Woods and Elmasian, 1986; Martin, Sigal, Kurtzberg and Stapells, submitted) and discriminative MMN ERPs (e.g., Aaltonen, Niemi, Nyrke and Tuhkanen, 1987; Kraus, McGee, Micco, Sharma, Carrell and Nichol, 1993; Sams, Aulanko, Aaltonen, and Näätänen, 1990) have been elicited using speech stimuli. The effects of hearing impairment on these ERPs elicited by speech stimuli have not been studied systematically. Limited work using a hearing-impaired population exists and demonstrates changes in ERPs to speech stimuli with hearing aids (Kurtzberg, 1989) and with cochlear implants (e.g., Kaga, Kodera, Hirota and Tsuzuka, 1991; Kraus, Micco, Koch, McGee, Carrell, Sharma, Wiet and Weingarten, 1993), but these studies used small numbers of subjects. Stapells, Kurtzberg, Martin, Gravel and Kreuzer (in preparation) examined changes in obligatory potentials with amplification in a large group of children with hearing loss. Results showed that there is large variability in the audiometric configurations associated with a present obligatory cortical response to speech sounds.

Polen (1984) found significantly longer latencies for N1, P2, N2 and P3, and smaller amplitudes for P2 and N2 in a group of hearing-impaired listeners compared to normal listeners on a /v/-/f/ contrast. Wall, Dalebout, Davidson and Fox (1991) found that only N1 amplitudes were significantly different between normal and hearing-impaired groups for /bɛ/-/dɛ/ and /bɛ/-/pɛ/ contrasts. Because this latter study employed only five listeners in each group, results must be interpreted cautiously. Kraus, McGee, Carrell and Sharma (1995) showed MMN results from two hearing-impaired subjects in response to a /da/-/ga/ speech contrast. One subject had "poor" behavioral discrimination of the contrast and one had "good" behavioral discrimination of the contrast. The first subject showed no MMN to the speech contrast, while the second subject did.

Martin, Sigal, Kurtzberg and Stapells (Chapter 3) carried out the first systematic investigation of the effects of decreased audibility in specific spectral regions on N1, N2, and P3 to speech sounds /ba/ and /da/. The study examined high-pass noise masked normal-hearing subjects so that

decreased audibility for specific spectral regions could be better controlled than is possible with hearing-impaired subjects. Results indicated that N1 showed small systematic changes in amplitude and latency as the masker cutoff frequency was lowered. N2, P3, and behavioral measures showed marked changes only for high-pass masker cutoffs below 2000 Hz. The results demonstrated that decreased audibility resulting from the noise masking affects the various ERP components in a differential manner. N1 was related to the presence of audible stimulus energy. It was present when the stimuli were audible, whether the stimuli were discriminable or not. In contrast, N2 and P3 were absent when the stimuli were not discriminable, even if they were audible.

In order to study the effects of controlled threshold elevations in specific spectral regions, with less of the variability present in sensorineural hearing-impaired populations, the present study also used high-pass noise-masked normal listeners. The data obtained from studies of noise-masked normal listeners may be useful in determining the optimal ERP parameters to apply to hearing-impaired listeners and may aid in the interpretation of their data. The purpose of this study was to investigate the effects of decreased audibility produced by high-pass noise masking on the cortical discriminative MMN as well as the obligatory N1 ERPs to the speech sounds /ba/ and /da/, and their relationship to behavioral measures of discrimination.

4C. Method

Subjects

Eleven normal adults (4 males, 7 females) aged 27 to 41 years (mean = 34 years) with no history of neurological disorder, participated. All subjects had hearing thresholds bilaterally of 20 dB HL (ANSI, 1989) or better from 250 through 4000 Hz. Additionally, acoustic immittance testing was performed prior to each session in order to rule out changing or abnormal middle-ear status. All subjects had a normal tympanogram and a present ipsilateral acoustic reflex (1000 Hz, 90 dB HL) in the test ear. Subjects signed consent forms after being informed of the nature of the experiment, and were paid for their participation.

Stimuli

The stimuli /ba/ and /da/ were selected for this study because they differ in place of articulation and thus differ in the frequency domain. They are the same stimuli used in our previous study of the effects of high-pass noise masking on cortical ERPs N1, N2 and P3 (Martin *et al.*, Chapter 3). The stimuli were created by digitizing natural tokens produced by a male talker. The tokens were then processed using linear prediction coefficient (LPC) analysis, and synthesized tokens were regenerated using the LPC polynomial roots (Maiste, Wiens, Hunt, Scherg and Picton, 1995). The tokens were digitized by the STIM portion of a Neuroscan system using a 30,000 Hz sampling rate (10,000 Hz anti-aliasing filter, 12 dB/octave), edited to 150-ms duration by eliminating the final portion of the steady-state vowel and windowing the offset of the vowel, and calibrated in peak-to-peak equivalent SPL (dB ppe SPL) relative to a 1000-Hz pure tone.

Spectrographic analysis was used to determine the frequencies of the formants and formant transitions for both /ba/ and /da/. The frequencies of the steady-state portion of the vowels were: F0 = 108 Hz, F1 = 674 Hz, F2 = 1140 Hz, and F3 = 2350 Hz. The transitions for /ba/ began at 328 Hz for F1, 1071 Hz for F2, and 2298 Hz for F3; the transitions for /da/ began at 362 Hz for F1, 1832 Hz for F2, and 2540 Hz for F3 (Chapter 3). The burst frequency information was similar for the two speech sounds, with energy from 1500-4800 Hz for /ba/ and 1200-4900 Hz for /da/. Thus, the primary difference between the stimuli are in the 1000 to 2000 Hz range. The stimuli were delivered using a digital-to-analog (D/A) rate of 30,000 Hz (10,000 Hz anti-imaging filter, 12 dB/octave), and presented to the right ear of the subjects at 65 dB ppe SPL. For ERP recordings, 600 stimuli per run were presented, and the runs were replicated, yielding a total of 1200 stimuli. For behavioral measures of discrimination, 200 stimuli, in total, were presented to each subject in each condition. Stimuli were presented with an onset-to-onset interstimulus interval (ISI) of 1100 ms, using an oddball paradigm whereby stimuli presented as standards had .8, and stimuli presented as deviants had .2, probability of occurrence. Both speech sounds were presented as standards and deviants in separate runs. Stimulus presentation order within a run was pseudo-

randomized, with the provision that two deviants could not occur successively, and that the first two stimuli could not be deviants. Presentation of the conditions was randomized for each subject.

Maskers

The speech sounds were presented in QUIET (no masking noise), and in conditions mixed with ipsilateral masking noise. The masking noise (Coulbourn white noise generator, model S81-02) was fed to a filter (Wavetek, model 852) with both channels set to high-pass and connected in series (96 dB/octave slope). After passing through the filter, the noise was attenuated and mixed with the stimulus (either the speech sounds for the ERP experiment or the pure tones for masked behavioral audiograms), and then fed to a passive attenuator and to an EAR-3A insert earphone. The level of broadband noise (BBN) required to fully mask behavioral perception of the speech sounds was determined for each subject by increasing the masking in 10-dB steps until the speech sounds were not heard. The masking level was then decreased by 10 dB and a bracketing approach initiated using a 1-dB step size. Masked threshold was defined as the level at which the speech sounds were inaudible 50% of the time. The masking noise was then increased by 7 dB above this level to ensure adequate masking of the speech sounds because the threshold for masking the ERPs is usually a few dB higher than the thresholds for masking perception (Stapells, Picton and Durieux-Smith, 1994). The BBN masking levels ranged from 75.5 to 83 dB SPL for the 11 subjects, with a mean level of 79.5 dB SPL. Without changing the noise level, the noise was subsequently high-pass filtered at 4000, 2000, 1000, 500 and 250 Hz.

EEG Recording

Seven EEG channels were recorded from surface electrodes placed at Fz, Cz, Pz, M1, M2, C3M (midway between C3 and M1), and C4M (midway between C4 and M2). The EEG channels were referenced to an electrode at the tip of the nose (Alho, Paavilainen, Reinikainen, Sams and Näätänen, 1986; Vaughan and Ritter, 1970). An eighth channel to monitor vertical eye movements and eye blinks (EOG) was recorded from electrodes over the right supraorbital ridge of the frontal bone and on the zygomatic bone under the right eye. An electrode placed on the neck served as ground. Electrode impedances were maintained below 5000 Ohms, with differences between

electrode pairs not exceeding 2000 Ohms. The seven EEG channels were amplified (gain = 20,000), filtered (0.1 to 100 Hz, 6 dB/octave), and digitized (568 Hz per channel, 512 points) using a 900-ms analysis time (including a 100-ms prestimulus baseline, against which amplitude measures were made). The EOG channel was filtered and digitized as above, but the amplifier gain was set to 5000. Single-trial ERP waveforms were saved for off-line baseline correction (-100 to 800 ms), digital filtering (30-Hz low-pass filter, 12 dB/octave), artifact rejection (± 100 μ V in any of the channels, and ± 75 μ V in the EOG channel) and averaging. ERPs were averaged separately for each stimulus, and averages were baseline corrected (-100 to 0 ms).

Behavioral Measures

Behavioral pure-tone audiograms obtained in QUIET and in the presence of the noise maskers were obtained for all of the subjects for 250 to 4000 Hz, using a Grason Stadler 1701 audiometer.

Measures of reaction time (RT) and percent correct discrimination were obtained separately from the ERP recordings by having the subject press a button in response to the deviant stimuli. Measures of median reaction time, and number of hit, false alarm, correct rejection and miss trials were obtained, and criterion-free measures of sensitivity (d') were calculated.

Calibration

The calibrations of the speech sounds, broadband noise, pure-tone stimuli (for the masked and nonmasked audiograms), and EEG amplifiers, were checked daily. The speech sounds were calibrated in dB ppe SPL (relative to a 1000-Hz tone, using the vowel portion of the syllables), and the noise and tones in calibrated dB SPL using a Brüel and Kjaer sound level meter (model 2209), Brüel and Kjaer coupler (model 4152) with a 2-cc adaptor (model DB0138). Amplifier channels were calibrated by sending a 50- μ V square wave, generated by the Grass amplifiers, through the amplifier channels and into the Neuroscan "SCAN". All channels were within 2.5 μ V of 50 μ V.

Procedure

The experiment consisted of EEG recordings, measures of behavioral responses to the speech sounds, and the audiograms. All testing was performed in a double-walled sound booth (Industrial Acoustics Corporation). For EEG recordings, subjects were instructed to read a book of their

choice and to ignore the speech sounds. They were also advised to minimize movements and eye blinks. Responses to the speech sounds were obtained in QUIET, in broadband noise, and in 250-, 500-, 1000-, 2000-, and 4000-Hz high-pass noise. The conditions were randomized, with the exception that one of the broadband noise conditions was tested first to ensure adequate masking of the speech sounds. For behavioral measures, subjects were instructed to press a button when they heard the deviant speech sound, and to place equal weight on the speed and accuracy of their button presses. Subjects were trained on the button-press task using two runs of 100 stimuli in the QUIET condition. Subjects were required to have at least 90% accuracy over both training runs for inclusion in the study. Behavioral measures were obtained in QUIET and in all of the noise masking conditions.

Data Analysis

After offline processing (baseline correction, artifact rejection and digital filtering), the single-trial responses were averaged so that responses to stimuli presented as standards and deviants were grouped separately. On average, across all subjects and all conditions, 85% of the responses to the standard and 85% of the responses to the deviant stimuli remained after artifact rejection. Replications were averaged together for each condition. Difference waveforms for each condition, used to measure the MMN, were obtained by subtracting averaged responses to the stimuli presented as standards from the averaged responses to the same stimuli presented as deviants. Derived responses (e.g., Don and Eggermont, 1978; Eggermont and Odenthal, 1974; Teas, Eldredge and Davis, 1962) representing narrow regions of the cochlea were calculated for each subject using the following subtraction process: 4000 minus 2000 Hz, 2000 minus 1000 Hz, 1000 minus 500 Hz, 500 minus 250 Hz, and 250 Hz minus BBN, giving derived responses representing one octave-wide bands centered on 2000, 1000, 500, 250, and 125 Hz (approximate), respectively. This procedure was completed separately for the waveforms to stimuli presented as standards and deviants, as well as for the difference waveforms.

Latency windows were developed using the data from the grand mean waveforms in order to measure the data from individual subjects. Response windows were 80-200 ms for N1 and 80-400 ms for the MMN. N1 was measured at Cz in the waveforms to the stimuli presented as standards; the MMN was measured at Cz in the difference waveforms. These measurement locations were chosen because largest amplitudes were seen at these sites in the grand mean waveforms. Because of the overlap in the response windows for N1 and the MMN, the data were inspected to ensure that the N1 and MMN measures were clearly differentiated.

Measurements were made on the average of the two replicated waveforms for each condition. Amplitude measures were determined at the point of largest amplitude for the peak within the response window. Latency measures for the MMN were obtained after the waveform was low-pass filtered at 15 Hz in order to smooth the waveform (Kurtzberg, Vaughan, Kreuzer and Fliegler, 1995). When a single peak was present, latency measures were taken at the center of the peak within the response window. In cases where a wave was double-peaked, latency measures were at the midpoint, and amplitude measures were taken from the larger peak. When multiple peaks were present, inversion at the mastoids was examined. If one peak inverted at one or both mastoids, then measurements were made from Cz for that peak. If no peaks showed clear inversion, but all were judged to be part of the MMN response, latency was taken from the midpoint.

Determination of response presence/absence required the agreement of two experienced judges. The presence of N1 was determined using the waveforms to the stimuli presented as standards. The presence of the MMN was determined using the difference waveforms. In order to be considered "present", both waves were required to be more negative in amplitude at frontocentral electrode sites compared to parietal electrode sites. Inversion at the mastoid electrode sites confirmed response presence, but lack of inversion was not used to indicate response absence. Additionally for the MMN, responses to stimuli presented as deviants and as standards were compared, and the waveform in response to deviant stimuli was required to be more negative within the response window than the waveform in response to stimuli presented as

standards. Finally, for the MMN, questionable waves with latencies more than 30 ms earlier than the MMN latency for a higher high-pass condition were determined to be absent. When waves were still considered questionable after using the above rules, the replicability of the waveforms was examined. If the wave was replicable, then it was judged as present. When a wave was judged to be absent, measures for it were given an amplitude of zero microvolts (except for the mean-MMN analysis, see below).

Additional measures were obtained for the MMN that were independent of response present/absent judgements. The mean amplitude of the MMN across a 100-ms response window was obtained from the data of individual subjects, regardless of the judges' rating of response presence/absence. These mean-MMN measures were taken by using a 100-ms window for each high-pass noise condition that began 20 ms past the latency of the peak of N1 in the grand mean data.

Amplitude measures were obtained for the derived response N1 data using the rules described above. Due to the extra subtraction process, the derived response MMN data were too noisy (e.g., Stapells, Picton and Durieux-Smith, 1994) for reliable peak amplitude and latency measures to be provided by visual observation. Therefore, only the mean-MMN amplitudes across a 100-ms window were obtained, with the window beginning 20 ms past the mean N1 derived response peak latency for each condition.

Two-way repeated measures analyses of variance (ANOVAs) (as a function of speech stimulus and noise condition), and three-way repeated measures ANOVAs (as a function of speech stimulus, ERP wave, and noise condition) were carried out on the amplitude and latency data. Main effects and interactions from the ANOVAs were considered significant if $p < .01$. Where appropriate, Greenhouse-Geisser epsilon correction factors (ρ) were applied to the degrees of freedom, and adjusted probabilities reported (Greenhouse and Geisser, 1959). For latency measures, the repeated measures ANOVAs were performed in a manner to maximize the number of conditions in the analysis. This required that some subjects be eliminated in order to avoid missing data. Conditions were eliminated, however, if fewer than half of the subjects remained.

Neuman-Keuls *post-hoc* measures were performed only when significant main effects or interactions were obtained. The *post-hoc* results were considered significant when $p < .05$.

Pearson product-moment correlation coefficients were calculated between the behavioral measures of discrimination and reaction time and N1 and MMN latency and amplitude. Results of correlational analyses were considered to be significant when $p < .01$.

4D. Results

Masked Audiograms

Behavioral masked and nonmasked pure-tone audiograms are displayed in Figure 1 (see Figure 1). Shown are the mean threshold data in dB SPL for the 11 subjects (top), and the corresponding standard deviations (bottom) (note: the Y-axis label of "threshold" indicates the same measure as indicated by "intensity" in Chapter 3, Figure 2). The masking noise produced moderate threshold elevations at and above the filter cutoff. Across all cutoff frequencies, the high-pass noise increased thresholds by an average of 42 dB at the high-pass cutoff and by 51 dB one octave above the cutoff frequency. Thresholds for frequencies below the cutoff frequency remained essentially unchanged.

Behavioral Sensitivity (d')

Figure 2 (top) shows the behavioral d' results calculated from button-press responses to deviant stimuli that were obtained in a session separate from the ERP measures (see Figure 2). These d' measures reflect the discriminability of the stimuli, and are displayed as a function of the noise masking condition. There is no significant difference in discriminability between the two speech stimuli [$F(1,10) = 1.09$; $p = .322$]. That is, listeners identified both /ba/ and /da/ as deviant stimuli equally well. Discriminability decreases as the high-pass noise cutoff decreases [$F(6,60) = 435.44$; $p < .001$; $\eta^2 = .4299$]. *Post-hoc* testing indicates that discriminability does not change until the noise cutoff frequency is below 2000 Hz. After this point, discriminability drops off sharply to near-zero levels.

Behavioral Reaction Time

The lower portion of Figure 2 shows the reaction time (RT) measures to the deviant stimuli. For both behavioral and ERP measures of latency, only conditions are plotted in which at least 6 of the 11 subjects had responses. There is no significant difference in reaction time to the two speech stimuli [$F(1,10) = 0.25$; $p = .627$]. Decreasing the high-pass cutoff frequency results in significantly increased RTs [$F(3,30) = 45$; $p < .001$; $\eta^2 = .3931$]. The RT results are similar to d' results in that *post-hoc* testing indicates no significant change in RT until the noise cutoff frequency is lowered below 2000 Hz.

Event-Related Potentials

The grand mean waveforms to /ba/ and /da/ (across all 11 subjects) are displayed in Figure 3 as a function of noise masking condition (see Figure 3). Responses recorded from Cz are displayed because responses in the grand mean data were largest in amplitude at this electrode site. N1 is clearly present in the QUIET through the 250-Hz high-pass noise conditions, but is absent in the BBN condition. The amplitude of N1 decreases and its latency increases steadily as the high-pass cutoff frequency is lowered.

The MMN is the increased negativity in the response to stimuli presented as deviants relative to the response to standards (e.g., Picton, 1995; Scherg, Vajsaar and Picton, 1989). In some of the waves, there is an early increase in amplitude that occurs at the latency of N1. This is an "N1 effect", caused largely by a longer time interval occurring between stimuli presented as deviants compared stimuli presented as standards (e.g., Scherg, Vajsaar and Picton, 1989). The MMN is best displayed in difference waveforms. The difference waveforms were obtained by subtracting individual's responses to stimuli presented as standards from their responses to the same stimuli presented as deviants. The grand mean difference waveforms for /ba/ and /da/ in the QUIET condition are displayed in Figure 4 (see Figure 4). Responses recorded at midline electrode sites Fz, Cz and Pz are shown by the thick lines, and responses recorded at the mastoid sites M1 and M2 are shown by the thin lines. The MMN to the speech sounds is larger at the frontocentral electrode sites (Fz and Cz) and smaller at the more posterior site (Pz). In these grand mean data,

inversion of MMN polarity is just visible in the M1/M2 traces. Polarity inversion of MMN at the mastoids was not always present in these data. There was large variability among the subjects for the polarity inversion, even in the QUIET condition. Some subjects showed clear polarity inversion of the MMN at the mastoids relative to Fz and Cz, some did not show clear polarity inversion, and some showed inversion at one mastoid, but not the other. For example, for /ba/ in the QUIET condition, four subjects showed clear MMN polarity inversion at the both mastoids, three subjects did not show polarity inversion, and four subjects showed polarity inversion at only one mastoid, but not the other. Examination of the data from individual subjects did not show an obvious relationship between the amplitude of the MMN and the presence/absence of polarity inversion.

Figure 5 shows the grand mean difference waveforms recorded from Cz in response to /ba/ and /da/, as a function of noise masking condition (see Figure 5). The negativity, representing the MMN, is present in the QUIET through 2000-Hz conditions, is not clear in the 1000-Hz condition, and is absent in the 500-Hz through BBN conditions. Waveforms obtained for the 1000-Hz condition are shown separately for subjects (RP) with a MMN response ($n=9$ for /ba/, $n=6$ for /da/) and for subjects (NR) with no MMN response ($n=2$ for /ba/, $n=5$ for /da/). Amplitude and latency changes as a function of noise masking condition begin with the 1000-Hz high-pass noise condition.

N1

N1 Amplitude

Figure 6 (see Figure 6) displays the effects of the noise conditions on N1 amplitude (top) and latency (bottom). N1 amplitudes are significantly larger in response to /ba/ than for /da/ [$F(1,10) = 11.11$; $p = .008$], even in the QUIET condition (-2.77 versus -2.39 μV). Amplitudes decrease gradually, but significantly, as the high-pass noise cutoff frequency is lowered [$F(6,60) = 16.52$; $p < .001$; $\eta^2 = .2882$]. *Post-hoc* analysis indicates that N1 amplitudes for the 500-Hz through BBN conditions are significantly smaller than for the QUIET through 1000-Hz conditions. There is no significant interaction between speech stimulus and noise condition [$F(6,60) = 1.07$; $p = .388$; $\eta^2 = .4902$].

N1 Latency

Responses to /ba/ show longer N1 latency than do those to /da/ [$F(1,10) = 12.14$; $p = .006$], even in the QUIET condition (122 *versus* 118 ms). Progressively lowering the cutoff frequency of the high-pass noise results in progressively increased N1 latencies [$F(4,40) = 76.86$; $p < .001$; $\eta^2 = .6982$]. *Post-hoc* analysis indicates that N1 latencies for the QUIET condition are significantly earlier than the 4000- through 500-Hz high-pass noise conditions; the latencies for the 4000- and 2000-Hz conditions are significantly earlier than those for the 1000- and 500-Hz conditions; and the latencies for the 1000-Hz condition are significantly earlier than those for the 500-Hz condition. As with amplitude, there is no significant interaction between speech stimulus and noise condition [$F(4,40) = 1.64$; $p = .184$; $\eta^2 = .4651$].

MMNMMN Peak Amplitude

The effects of noise condition on MMN peak amplitude (top) are displayed in Figure 7 (see Figure 7). Although the MMN to /ba/ (mean = $-2.29 \mu V$) is larger in amplitude than the MMN to /da/ (mean = $-1.46 \mu V$) in the QUIET condition, across all conditions there is no significant effect of speech stimulus on MMN amplitude [$F(1,10) = 0.93$; $p = .359$]. There is a significant effect of noise condition on MMN amplitude [$F(6,60) = 17.45$; $p < .001$; $\eta^2 = .4803$]. *Post-hoc* analyses indicate that MMN amplitude drops significantly when the noise cutoff frequency is lowered to 1000 Hz and below. There is no significant interaction between speech stimulus and noise condition [$F(6,60) = 1.77$; $p = .120$; $\eta^2 = .4766$].

MMN-Mean Amplitude

The mean amplitude of the MMN over a 100-ms window, determined for all waves regardless of response presence/absence, was also calculated. Mean results ($n=11$) and corresponding standard deviations are shown in Table 1 (see Table 1). Statistical analysis of this data indicated a main effect of noise condition on mean-MMN amplitude [$F(6,60) = 5.49$; $p < .001$; $\eta^2 = .5629$]. *Post-hoc* testing indicated that mean-MMN drops significantly for the 1000-Hz high-pass noise condition and below.

MMN Peak Latency

There is no significant effect of speech stimulus on MMN latency (Figure 7, bottom) [$F(1,4) = .30$; $p = .615$]. There is a significant effect of noise condition on MMN latency [$F(3,12) = 10.03$; $p = .001$; $\eta^2 = .5936$]. *Post-hoc* analyses indicate that lowering the high-pass noise cutoff frequency to 2000 Hz results in small, but nonsignificant, latency increases. Lowering the high-pass noise cutoff frequency further to 1000 Hz results in a large latency increase that is significant by *post-hoc* analysis.

MMN Variability

In the 1000 Hz high-pass noise condition, some subjects showed a MMN response, while others did not. Responses from subjects with MMNs judged as present (RP) were therefore subsequently averaged separately from responses from subjects judged to have no MMN response (NR) (Figure 5). Shown this way, the MMN in the 1000-Hz high-pass noise condition for the grand mean of the response-present data is more clear. Specifically, in the 1000-Hz high-pass condition, nine subjects had MMN responses judged as present, and two had MMNs judged as absent, in response to the speech sound /ba/. For /da/, six subjects had present MMNs and five had absent MMNs. Six of the seven subjects with absent MMNs for the 1000-Hz high-pass condition had behavioral d' scores of 1.0 or better for that condition, suggesting the behavioral measure of discrimination was more sensitive than the ERP measure (i.e., MMN) of discrimination for this condition. In our previous study, all of the subjects had a present P3 for the 1000-Hz high-pass noise condition (across both speech stimuli), though four had a d' score less than 1.0 (Chapter 3).

The MMN is small and quite variable, even in the QUIET condition. For example, although present for all subjects in the QUIET condition, MMN peak amplitudes to /ba/ in the QUIET condition ranged in individual subjects from -0.45 to -3.60 μV , and latencies ranged from 158 to 260 ms. The mean-MMN amplitude over a 100-ms window ranged from -0.03 to -2.47 μV . Responses to /da/ in the QUIET condition ranged in individual subjects from -0.40 to -3.24 μV (MMN peak amplitude), latencies ranged from 151 to 251 ms, and mean-MMN amplitude over a 100-ms window ranged from 0.02 to -1.98 μV . For the 1000-Hz condition, MMN peak amplitude,

averaged across both speech stimuli, ranged in individual subjects from 0 to -2.59 μV ; mean-MMN amplitudes ranged from +1.92 to -2.00 μV ; and latencies, in those subjects judged to have present responses, ranged from 183 to 390 ms.

Correlations between ERP and Behavioral Measures

The relationships between the ERP and behavioral measures of discrimination were examined using Pearson product-moment correlations (see Table 2). Only those RTs with a corresponding d' score of 1.0 or better were included, eliminating the RT scores reflecting guessing. Behavioral d' scores show significant correlations with both MMN amplitude and N1 amplitude, though the correlation is better with the MMN. In contrast, d' shows a stronger relationship to N1 latency than to MMN latency. Behavioral reaction time measures are only weakly correlated to ERP amplitude and latency measures, with the exception of N1 latency, which showed a moderate correlation with RT. All of the correlations reached statistical significance, except for the correlation between RT and ERP amplitudes (N1, MMN). Sensitivity measures (d') show a stronger relationship to the ERP measures than do the RT measures. The d' score reflects stimulus discrimination, and takes into account a subject's false alarm rate.

Comparison of ERP and Behavioral Measures

Figure 8 (see Figure 8) summarizes the results of this study, and compares them to the P3 results from our previous study (Chapter 3). The data are normalized to results for the QUIET conditions (d' & amplitude: change from QUIET in percent; RT & ERP latency: latency change from QUIET in ms). The data are collapsed across the two speech stimuli as there was no significant difference between the stimuli for most of the measures. Measures of percent change from the QUIET condition (response strength) are shown in the top graph, and measures of latency change from the QUIET condition are shown in the lower graph. The peak-MMN, P3 and d' scores show similar changes in response strength as the high-pass noise cutoff is lowered. There is no change until the noise cutoff frequency is lowered to 1000 Hz. At this point, response strength sharply decreases, and continues to drop as the noise cutoff frequency is lowered further. A similar pattern is seen for latency change, with no significant changes seen until the 1000-Hz

condition. In contrast, N1 results show a different pattern of change as a function of high-pass masking condition. Amplitudes drop steadily until the speech sounds are inaudible (BBN condition). Similarly, N1 latency increases are steady and gradual as the cutoff frequency of the high-pass noise is lowered.

Supporting these findings, a three-way repeated measures ANOVA comparing the response strength of d', N1 and MMN as a function of speech stimulus and high-pass noise condition indicates a significant measure x condition interaction [$F(12,120) = 8.76$; $p < .01$; $\eta^2 = .5039$]. *Post-hoc* analysis indicates this effect was due to a difference in N1 relative to d' and the MMN at the 1000- and 500-Hz masker cutoff frequencies. A three-way repeated-measures ANOVA comparing the normalized latency shift from the QUIET condition for RT, N1 and the MMN as a function of speech stimulus and noise condition indicates a trend for a measure x condition interaction [$F(6,24) = 6.27$; $p = .04$; $\eta^2 = .4043$]. Inspection of the findings suggests this trend is due to a difference between N1 compared to RT and the MMN at the 1000-Hz noise cutoff frequency.

Additional support for differences between the N1 and the MMN and behavioral results is provided by comparing the frequency at which response amplitude across individual subjects decreased by 50%. The mean frequency at which response strength dropped off by 50% was 352 Hz for N1, 818 Hz for d', and 1102 Hz for the MMN. ANOVA results indicated a main effect for measure [$F(2,20) = 8.55$; $p = .002$; $\eta^2 = .7009$], with *post-hoc* analysis indicating the results for N1 are significantly different from those for d' and the MMN.

Finally, in addition to the above ANOVAs performed on data from the present study, normalized amplitude and latency results for the MMN were compared to those for P3 from the previous study (Chapter 3), as a function of stimulus and masking condition, using a three-way ANOVA. Results indicate no significant main effect of measure, indicating no difference in the effect of the high-pass noise masking on MMN compared to P3 amplitude [$F(1,19) = 1.95$; $p = .179$] or latency [$F(1,13) = 0.00$; $p = .99$].

Derived Responses

The grand mean derived response waveforms are displayed in Figure 9 (see Figure 9). N1, as measured from the derived response waveforms to stimuli presented as standards, contains contributions from a wide frequency range along the cochlea, being clearly present for center frequencies from 2000 through at least 250 Hz. The MMN, as measured from the derived response difference waveforms, contained contributions from a more narrow region of the cochlea. Derived MMN waveforms were maximal for center frequencies of 500 - 1000 Hz for /ba/, and for a center frequency of 1000 Hz for /da/. Positive waves in the derived response difference waveforms are not, by usual definition, MMN (e.g., /da/ derived response at 500 Hz).

Figure 10 displays the derived response N1 peak amplitude (top) and derived response mean-MMN amplitude (bottom) profiles as a function of center frequency for /ba/ and /da/ (see Figure 10). N1 contained contributions from 2000 Hz down to <250 Hz, though the contribution was maximal for a center frequency of 250 Hz. The MMN for /ba/ contained contributions from the 1000-, 500- and <250-Hz regions of the cochlea, with maximal contribution from the 500-Hz region. For /da/, the MMN contained contributions from the 2000- through 500-Hz regions, as well as the <250-Hz region, with maximal contribution from the 1000-Hz region. The <250-Hz MMN for /da/ is somewhat early in latency, possibly reflecting an N1 contribution. This can be seen in the waveforms of Figure 9.

An ANOVA was performed on the derived response amplitude data for N1. Results indicated a trend toward an effect of derived band center frequency on derived N1 amplitude [$F(5,50) = 3.65$; $p = .03$; $\eta^2 = .5140$]. Examination of the data indicated that the derived N1 amplitude profile was maximal for the cochlear region centered around 250 Hz. Variability for the derived response mean-MMN data was too high to provide acceptable power for statistical analysis, and an ANOVA on these data was not considered appropriate.

4E. Discussion

The high-pass noise maskers resulted in decreased audibility in specific spectral regions, similar to that seen with steep high-frequency hearing losses. As the noise cutoff frequency was lowered, the portion of the audiogram showing decreased audibility changed systematically, to include high-frequency regions, to including high-, mid- and low-frequency regions. The threshold elevations produced by the high-pass noise are almost identical to those obtained in our previous study (Chapter 3).

This decreased audibility results in decreased ERP amplitudes and increased ERP latencies, along with lower behavioral d' values and increased reaction times. For the stimuli used in this study (/ba/, /da/), the effects of the high-pass noise are greatest beginning when the spectral region of 1000-Hz and below is masked. This is the frequency region where the primary acoustic cues differentiating /ba/ from /da/ occur (i.e., second formant transition). Specifically, in the 2000-Hz high-pass noise condition, most of the F2 transitional information for /da/ is present, and all of the F2 transitional information is present for /ba/. As a result, little change in behavioral and ERP measures of discrimination is seen. In the 1000-Hz high-pass noise condition, the F2 transition for /da/ is masked, and a good deal of the F2 transition for /ba/ may be masked. This masking of the F2 transitions results in changes in behavioral and ERP measures of discrimination.

Behavioral Measures

The effects of the moderate threshold elevations produced by high-pass noise masking on behavioral d' scores and RTs are similar to those seen in our previous study (Chapter 3). The d' scores decrease, and RTs increase significantly when the noise cutoff frequency is below 2000 Hz and the frequency regions containing the second and third formant transitions for the speech sounds are masked.

ERP Measures

Decreased audibility of the speech sounds produced by high-pass noise masking results in increased latencies and decreased amplitudes of the ERP peaks. No studies examining the effect of high-pass noise masking on the MMN or on N1 in an ignore condition have previously been published.

N1

Results for N1 are similar to those of our previous study (Chapter 3), even though subjects ignored the stimuli for this study, whereas the previous study required subjects to attend to the stimuli. N1 shows amplitude changes beginning at the 500-Hz masker cutoff frequency. N1 latency changes were gradual, and significant changes began as early as the 4000-Hz masker condition, and proceeded steadily thereafter. N1 amplitudes were significantly larger for /ba/ than for /da/; latencies, however, were longer for /ba/ than for /da/. The larger amplitude for responses to /ba/ can perhaps be explained by examining N1 responses to tones of different frequencies. N1 is larger in response to low-frequency tones than for high-frequency tones (e.g., Picton, Woods and Proulx, 1978). The formant transition frequencies for /ba/ are lower in frequency than those for /da/, therefore, the amplitude difference for the two stimuli may be due to the lower frequency content of /ba/ relative to /da/. This lower frequency content of the formant transitions for /ba/ relative to /da/ may also explain the N1 latency difference which may be due to traveling wave delays at the cochlear level for /ba/ relative to /da/ which are manifested at the cortical level (Békésy, 1960; Hind, 1953). Additionally, different cortical representation of the two speech sounds due, in part, to their differing frequency content is likely (e.g., Mendelson and Cynader, 1985; Phillips and Irvine, 1981; Ponton, Don, Waring, Eggermont and Masuda, 1993; Sams and Näätänen, 1991; Steinschneider, Arrezzo and Vaughan, 1990). N1 latencies for /ba/ in our previous study (Chapter 3) were also longer than for /da/, but amplitudes were not significantly different.

The derived response technique has been used in electrocochleography and auditory brainstem response testing (e.g., Don and Eggermont, 1978; Stapells et al., 1994; Teas, Eldridge and Davis, 1962) to obtain evoked potentials originating from a narrowband region of the basilar membrane. To our knowledge, the technique has not been used previously for cortical auditory ERPs. As seen in Figures 9 and 10, derived contributions to N1 came from a broad range of frequencies. Contributions were seen in at least the 1000-Hz through <250-Hz center frequency bands.

MMN

The MMN showed amplitude and latency changes beginning with a high-pass masker cutoff of 1000 Hz, the cutoff value at which the second formant frequency transition differentiating /ba/ from /da/ is partially masked. There was no effect of speech stimulus on MMN amplitudes or latencies, although in the QUIET condition, MMN amplitude to /ba/ appears larger than to /da/. This is reversed, however, for the 4000-Hz high-pass noise condition, where MMN amplitude to /da/ appears larger than to /ba/. Interestingly, Maiste (1989) also reported slightly longer N1 latencies for /ba/ than for /da/ (121 versus 118 ms). Maiste and colleagues, however, found that the MMN was larger when /da/ was the deviant stimulus than when /ba/ was the deviant stimulus (Maiste et al., 1995). The stimuli used in this study are the same as those used by Maiste and colleagues (Maiste, 1989; Maiste et al., 1995), except that in the present study, only endpoint stimuli were selected, and our stimuli were edited to 150-ms duration.

The scalp distribution of the MMN in the present study was slightly more posterior (maximal at Cz rather than at Fz) than is usually reported (e.g., Alho, 1995), though the difference in amplitude between these electrode sites was quite small. For example, the amplitude of the grand mean waveform (averaged across the two speech sounds) was -1.11 μ V at Fz, and -1.26 μ V at Cz, a difference of only 0.15 μ V. The scalp location of maximal amplitude was not consistent across the individual subjects. Some subjects showed maximum amplitude at Fz, and others at Cz. The variability is likely accounted for by differences in the orientation of the MMN generators in individuals, and possibly by the slightly different cortical representation for speech, at least for the specific speech sounds used for this study (Lang, Eeola, Korpilahti, Holopainen, Salo, and

Aaltonen, 1995). ERP peak N2b did not account for the variability, as subjects were ignoring the stimuli, and the wave was not followed by P3b.

The derived response MMN showed contributions from center frequencies of 1000 and 500 Hz for /ba/, and 2000 - 500 Hz for /da/. There also appears to be a small contribution for the center frequency <250 Hz. Based on its early latency, however, this contribution from <250 Hz is likely due to N1, as can be seen by inspection of the standard and deviant waveforms in Figure 9. The higher frequency contributions to the derived MMN for /da/ compared to /ba/ is likely due to the higher frequency nature of the second and third formant frequency transitions for /da/ compared to /ba/. The effects of derived-band center frequency on the MMN could not be assessed statistically due to the small amplitude and large variability of the derived MMN. The additional subtraction required to obtain the derived MMN increased the background noise by a factor of 1.4 ($\sqrt{2}$) (e.g., Stapells et al., 1994). This decrease in signal-to-noise ratio would decrease the statistical power of our subsequent analyses.

N1 versus MMN The high-pass masking noise had a differential effect on N1 and the MMN. For those noise masking conditions where responses were present (4000 through 1000 Hz), the noise masking resulted in latency increases of 14 ms for N1 and 122 ms for the MMN. Therefore, the later the wave, the greater the effect of high-pass noise masking on latency. Results from our previous study (Chapter 3) also showed that later waves were affected more by noise masking. In the present study, amplitude changes showed a similar pattern, with greater changes seen for the MMN relative to N1. With data collapsed across stimulus, when the high-pass noise cutoff was lowered from 2000 to 1000 Hz, N1 amplitude dropped by 0.03 μ V and N1 latency increased by 7 ms. For MMN, however, amplitude dropped by 0.92 μ V and latency increased by 96 ms.

Relationship between ERP and Behavioral Results

Correlations

Behavioral measures of sensitivity (d') were correlated both to ERP amplitudes and to ERP latencies. Behavioral reaction time measures were moderately correlated to ERP latencies, but their relationship to amplitude measures was quite weak. The strong relationship shown between

d' and N1 may reflect that although d' measures stimulus discrimination, stimulus discrimination itself is correlated to stimulus audibility. The more audible the sounds, the easier it is to discriminate them. N1 and d' , therefore, may both index stimulus audibility. This strong relationship between d' and N1 was also seen in our previous study, where correlations were .50 for N1 amplitude and -.67 for N1 latency (Chapter 3). The progressive increase in the relationship between behavioral measures of discrimination and the ERP peaks seen in the previous study, such that later peaks had stronger correlations with behavioral measures, however, is not apparent in the present study. This may be due to the fact that ERP recordings in the previous study were obtained while subjects were paying attention to the speech stimuli. Active, task-related processing of sounds is mediated by attention (e.g., Picton, Campbell, Baribeau-Braun, and Proulx, 1978; Picton and Hillyard, 1974; Picton, Hillyard and Galambos, 1976), and it makes sense that behavioral measures of discrimination would be better correlated with ERP peaks (N2 and P3) that are associated with conscious detection of stimulus change. In the present study, subjects were tested while they read a book and ignored the speech sounds. The MMN does not require attention to the task, and therefore provides us with information on whether the brain has noted a stimulus change at a pre-attentive level. Correlations between behavioral (d') and ERP (N1 and MMN amplitude) measures of response strength were fairly strong, with the correlation for N1 similar to the previous study, though the correlation with the MMN was poorer than the correlation with P3 obtained in the previous study.

It is possibly more appropriate to compare the correlations between behavioral measures of discrimination and the MMN to results from the previous study for N2, rather than P3. N2 comprises both the MMN and the N2b response (e.g., Näätänen, Simpson and Loveless, 1982). N2b has been associated with bringing a stimulus change into consciousness (Näätänen, Simpson and Loveless, 1982; Ritter, Paavilainen, Lavikainen, Reinikainen, Alho, Sams and Näätänen, 1992). The correlation between d' and MMN amplitude was .68, and in the previous study the correlation between d' and P3 amplitude was .78. The correlation between d' and N2 amplitude, however, was .63, which is closer to that seen in the present study. The correlations between RT and MMN

latency were .31 in the present study. The correlation of RT with P3 latency was .56 in the previous study, whereas for N2 latency, the correlation was .41, much closer to the results of the present study.

The correlations between d' and the ERPs were better than those between RT and the ERPs. In contrast to percent scores, behavioral d' scores correct for false alarm rate. For correlations between RT and the ERPs, we only accepted RTs that were associated with a d' score of 1.0 or more in an attempt to eliminate spurious RT data associated with guessing. Using this criterion, the lower correlations with RT probably cannot be explained by false alarm responses. For this study with N1 and MMN, it seems that accuracy (as measured by d') better predicts ERP results than does the timing of the behavioral measures (as measured by RT).

Comparison of Measures

A comparison of changes in the behavioral measures with the various ERP measures as a function of high-pass noise masking condition reveals that N1 changes are different from those seen for MMN, P3 (from the previous study), and behavior. N1 shows slow, systematic decreases in amplitude and increases in latency as the cutoff frequency of the high-pass masker is lowered. The MMN, P3, and behavioral measures all show a marked change beginning at the 1000-Hz high-pass condition. N1 appears to reflect only audible stimulus energy, being present whether or not the speech sounds were discriminable, and being absent when the speech sounds were not heard. The MMN, P3, and behavioral measures were clearly related to the discrimination of the speech sounds, with MMN and P3 being present only for those conditions that were behaviorally discriminable. Additionally, both waves (MMN, P3) were correlated with behavioral measures, though correlations were greater for P3, the wave that depends on conscious detection of stimulus differences. The fact that the MMN also was correlated with behavioral measures is interesting, and supports other studies showing a strong relationship between the MMN and behavioral discrimination performance (e.g., Sams, Paavilainen, Alho and Näätänen, 1985).

In the present study, not all subjects had a present MMN when the noise masker was lowered to 1000 Hz. Of those subjects with absent MMNs at this noise cutoff frequency, all but one had behavioral d' scores greater than 1.0, indicating they could discriminate the stimuli. This indicates that the behavioral measure of discrimination was more sensitive than the MMN measure for these subjects in this noise condition. In part, the absent MMNs were likely due to poor ERP signal-to-noise ratios. The amplitudes of the MMN in this study were small. Ideally, increasing the number of trials, decreasing the probability of the deviants, and increasing stimulus presentation rate (e.g., Lang, Eerola, Korpilahti, Holopainen, Salo and Aaltonen, 1995) might have improved the signal-to-noise ratio sufficiently to measure an MMN for the 1000-Hz high-pass noise condition for those subjects with MMNs judged as absent. The MMN generally does agree with perceptual measures, but a larger number of trials may be required for more difficult conditions (such as the 1000-Hz high-pass noise condition) in order to identify the MMN (e.g., Sams *et al.*, 1985). The fact that the MMN disappeared into the noise floor in this 1000-Hz high-pass condition, whereas N1 did not, indicates that N1 and the MMN respond differently to the noise masking, especially given that those subjects with present MMNs showed large changes in amplitude and latency at this cutoff frequency.

ERP Evaluation of Speech Processing at Different Levels in the Auditory System

Decreased audibility in specific spectral regions results in smaller ERP amplitudes and behavioral d' scores, and longer ERP latencies and behavioral reaction times, at least for /ba/ and /da/. This suggests that decreased audibility resulting from the masking noise alters brain processes associated with the processing of speech sounds. The time required to process the sounds is lengthened, and the strength of the response to the speech sounds is reduced. The maskers affect N1 differently than the MMN, P3 or behavioral measures. Studied together, these ERPs provide a window into brain processing of the /ba/-/da/ speech contrast, and make possible evaluation of speech processing within different levels of the auditory system. N1 indexes the processing of audible speech sound energy at the cortical level. On average, N1 responses occurred between 108 ms (QUIET condition) and 139 ms (500-Hz high-pass noise condition). The

MMN indexes discrimination between sounds at a pre-attentive level. On average, MMN changes occurred between 203 ms (QUIET condition) and 325 ms (1000-Hz high-pass noise). P3 indexes speech sound discrimination at a conscious level. On average, P3 changes occurred between 398 (QUIET) and 439 ms (1000-Hz high-pass noise) (Chapter 3). Behavioral measures also index discrimination at a conscious level. Changes in RT occurred between 381 ms (QUIET) and 533 ms (1000-Hz high-pass noise). As would be expected, the processing of audible speech energy (N1) occurs earlier than does processing of stimulus difference at a pre-conscious level (MMN), and that conscious processing of stimulus change occurs even later (P3 and behavioral measures). Thus, it would appear that these ERP and behavioral measures allow us to examine speech sound processing at different levels within the brain.

Advantages and Disadvantages of the MMN

One disadvantage of the MMN in this study was its small amplitude and large variability. As a result, the data were noisy, and the data from individual subjects were sometimes difficult to interpret. Additionally, the results did not always reach statistical significance. Overall, however, the general effects of high-pass noise masking on the MMN were clearly seen. In other words, the mean data, as seen in the graphs, showed consistent effects.

A large advantage of the MMN is that it reflects pre-attentive speech sound processing (e.g., Näätänen, 1990). Active subject participation is not required. This is easier for subjects. Although they must sit quietly and read for the duration of testing, they are not required to attend to a boring, repetitious task for long periods of time. P3, on the other hand, reflects the psychological significance of speech sound processing (e.g., Chapter 3). It is large in amplitude and not difficult to recognize, but requires active subject participation. These requirements are not feasible for all patient populations.

Implications

To our knowledge, no published study has examined MMN amplitudes and latencies as a function of hearing loss. This study systematically examined the effects of decreased audibility, produced by high-pass noise masking in specific spectral regions, on N1 and MMN amplitudes and

latencies to the speech sounds /ba/ and /da/. The advantage of using normal-hearing subjects is that decreased audibility could be examined with less of the variability due to factors that are difficult to control, such as altered processing of frequency, intensity and temporal information present in subjects with sensorineural hearing loss (e.g., Festen and Plomp, 1983; Scharf, 1978; Thibodeau, 1991). Studies are now in progress in our laboratory examining the effects of decreased audibility on cortical ERPs (N1, MMN, N2, P3) in subjects with sensorineural hearing loss.

The present study provides further evidence that N1 is related to the presence of audible speech energy. It was present when speech sounds were audible, whether or not they were discriminable. The derived response N1 had contributions from a broad range of frequencies represented in the cochlea. This suggests that if there is audible stimulus energy for any of these frequencies, an N1 will be elicited. The MMN, as expected, was related to the discrimination of audible speech stimuli, as was P3 from our previous work (Chapter 3). The derived response results indicate the MMN came from a more narrow region of the cochlea than did N1. For the discrimination of /ba/ and /da/ for this study, the critical frequency region was approximately 1000 Hz. This suggests that if the stimulus is not audible in this frequency region (as may occur with sensorineural hearing loss), no MMN will be elicited.

The clinical utility of the MMN is limited by the small, variable responses obtained. Unfortunately, recording the MMN is not always an easy task. The MMN is reasonably easy to recognize in group data, but due to its small amplitude and large variability, it may be difficult to record enough trials to make the MMN a practical clinical tool for individual subjects. Until the problems associated with the assessment and recognition of the MMN in individual subjects have been resolved, it is a more suitable tool for study of groups of subjects. For a single subject, MMN measures for a single speech contrast would require over an hour of testing. For example, in this study, recording the MMN for each high-pass noise condition required approximately 40 minutes. Additionally, placement of the electrodes required 20 to 30 minutes. In order to increase the efficiency of our testing by increasing the signal-to noise ratio of the recordings, our MMN test

protocols have been changed since this study was completed. We are now using a shorter ISI (approximately 600 ms), a decreased probability of deviant occurrence (.1), and a larger number of sweeps in each run (1000). Even with these changes, the recording time is largely unchanged, though the waveforms obtained are more clear. Recording for multiple speech contrasts requires more time than most clinical patients are willing to provide. For measures of auditory discrimination at or near hearing (or psychophysical) threshold, it is likely that a much greater number of sweeps will be required in order to identify the small MMN that is present at or near threshold. Similarly, for subjects with hearing loss, a larger number of sweeps will likely be required.

Another clinical implication of the MMN is for potential application to pediatric populations. The MMN has been demonstrated in babies (e.g., Alho, Sainio, Sajaniemi, Reinikainen, and Näätänen, 1990; Cheour-Luhtanen, Alho, Kjuala, Sainio, Reinikainen, Renlund, Aaltonen, Eerola and Näätänen, 1995), although it is quite variable (e.g., Kurtzberg, Vaughan, Kreuzer and Fliegler, 1995). Interpretation of data from young children is further complicated due to rapid maturation and corresponding changes in cortical ERP morphology (e.g., Kurtzberg, Hilpert, Kreuzer and Vaughan, 1984; Novak, Kurtzberg, Kreuzer and Vaughan, 1989; Steinschneider, Kurtzberg and Vaughan, 1992). Much research is required before the MMN can be applied to the pediatric clinical population.

4F. Acknowledgements

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Table 1. Average mean-MMN amplitudes across the subjects (n=11) are displayed for /ba/ and /da/ for all of the noise masking conditions along with corresponding standard deviations.

/ba/	QUIET	4000 Hz	2000 Hz	1000 Hz	500 Hz	250 Hz	BBN
mean	-.96	-.82	-.64	-.29	.61	-.24	.14
s.d.	.82	.71	1.13	1.21	1.01	.81	.62
/da/							
mean	-1.04	-.73	-.80	-.14	.16	.04	.32
s.d.	.74	1.17	.83	1.17	1.18	.90	.91

Table 2. Results of correlational analyses between behavioral [sensitivity (d') and reaction time (RT)] and ERP [N1 and MMN] measures. Shown are Pearson product-moment correlation coefficients (r) and number of measures (N).

		AMPLITUDE		LATENCY	
		N1	MMN	N1	MMN
d'	r	.53*	.68*	-.76*	-.46*
	N	154	154	120	85
RT	r	-.18	-.13	.42*	.31*
	N	87	87	87	77

* p < .01

Figure Captions

Figure 1. Mean (top) and standard deviation (bottom) behavioral pure-tone masked and nonmasked audiograms (across the 11 subjects) are displayed in dB SPL. Audiograms are shown for the QUIET (nonmasked) condition, 4000-Hz through 250-Hz high-pass noise masked conditions, and the broadband noise (BBN) masked condition.

Figure 2. The top portion of the figure displays the effects of high-pass noise condition on sensitivity (d'), along with corresponding standard deviations. Circles indicate results for /ba/ and triangles indicate results for /da/. The lower portion of the figure displays the effects of high-pass noise condition on reaction time (RT), along with corresponding standard deviations.

Figure 3. Grand mean waveforms recorded to stimuli presented as standards (thin line) and deviants (thick line) are displayed for /ba/ and /da/ as a function of high-pass noise masking condition. The data shown are from the electrode at Cz.

Figure 4. Grand mean difference waveforms from Fz, Cz and Pz electrode sites are displayed for /ba/ and /da/ in the QUIET condition. Waveforms recorded from mastoid electrode sites (thin lines: M1, M2) are superimposed on the waveforms recorded from Fz.

Figure 5. Grand mean difference waveforms from Cz are displayed for /ba/ and /da/ as a function of high-pass noise masking condition. RP indicates a waveform averaged only for subjects with a present MMN. NR indicates a waveform averaged only for subjects with no MMN.

Figure 6. N1 amplitudes (top) and latencies (bottom) are displayed as a function of high-pass noise masking condition. Circles indicate responses to /ba/ and triangles indicate responses to /da/.

Figure 7. Peak-MMN amplitudes (top) and latencies (bottom) are displayed as a function of high-pass noise masking condition. Circles indicate responses to /ba/ and triangles indicated responses to /da/. The number of subjects included for the 1000-Hz condition are indicated ($n=9$ for /ba/, $n=6$ for /da/). Data from the remaining subjects were eliminated as they were judged to have no MMN in the 1000-Hz high-pass noise condition.

Figure 8. Response strength (top) and latency change (bottom) normalized to the QUIET condition, are displayed as a function of high-pass noise masking condition. N1 is indicated by squares, MMN is indicated by circles, P3 is indicated by diamonds (results from Chapter 3), and behavioral responses are indicated by the letter "B". Data are pooled across /ba/ and /da/.

Figure 9. Grand mean derived responses for each high-pass noise masking condition are displayed for /ba/ and /da/. For each condition, derived responses to stimuli presented as standards (thin lines) and deviants (thick lines) are shown (top) along with difference waveforms (bottom).

Figure 10. Derived response amplitude profiles are displayed as a function of center frequency for N1 peak amplitude (top) and mean-MMN amplitude (bottom). The shaded portion indicates the portion of the graph associated with no response (i.e., non-negative voltage measures). Circles indicate responses to /ba/ and triangles indicate responses to /da/.

Figure 1

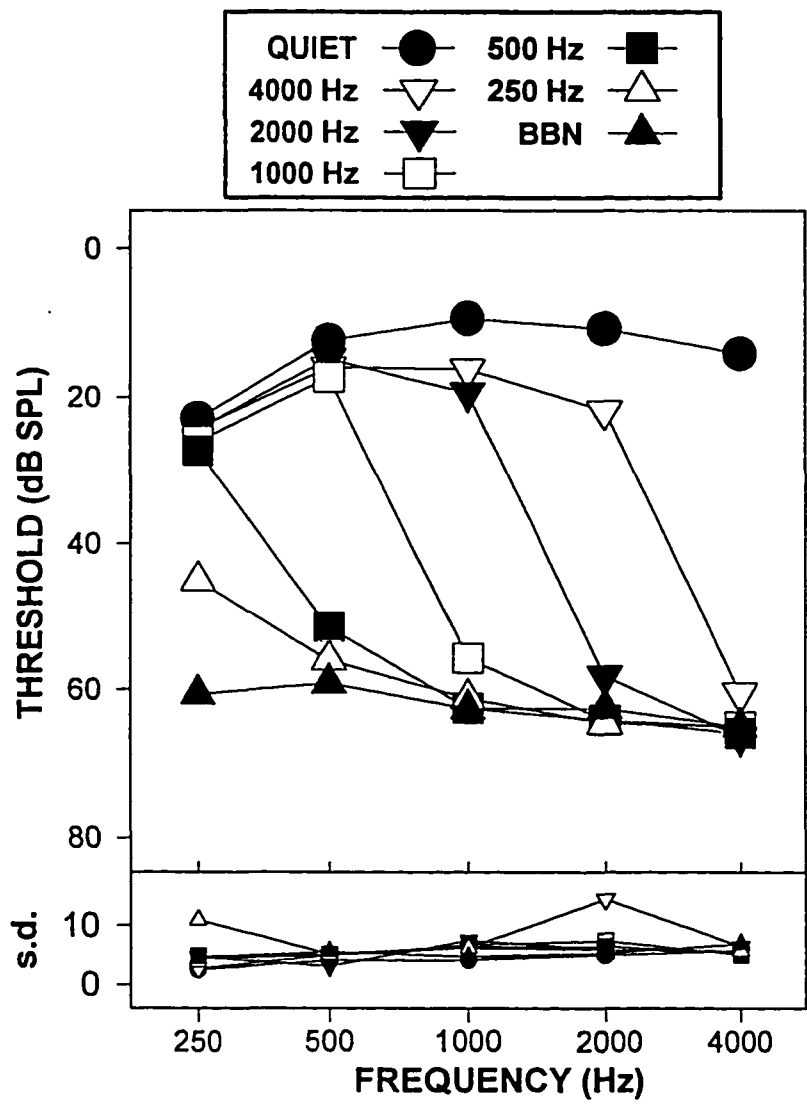


Figure 2

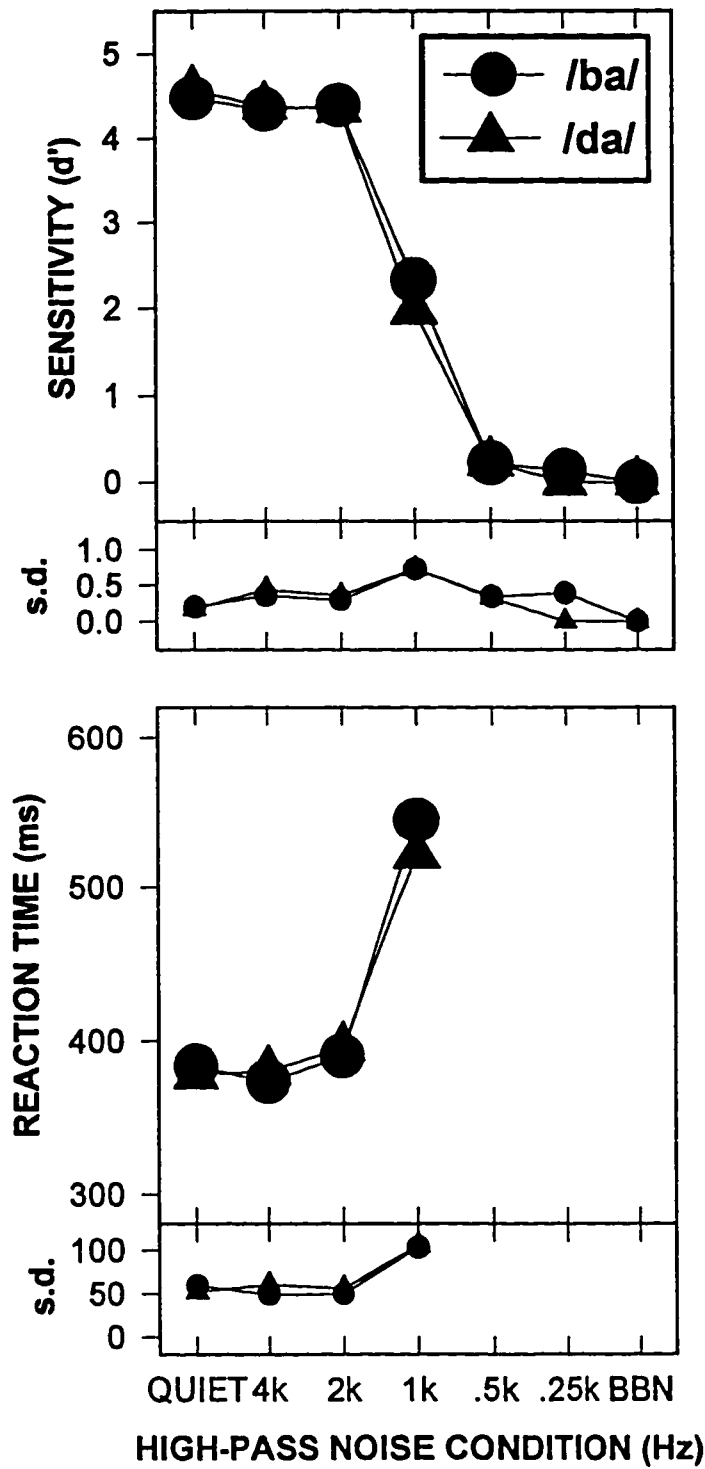


Figure 3

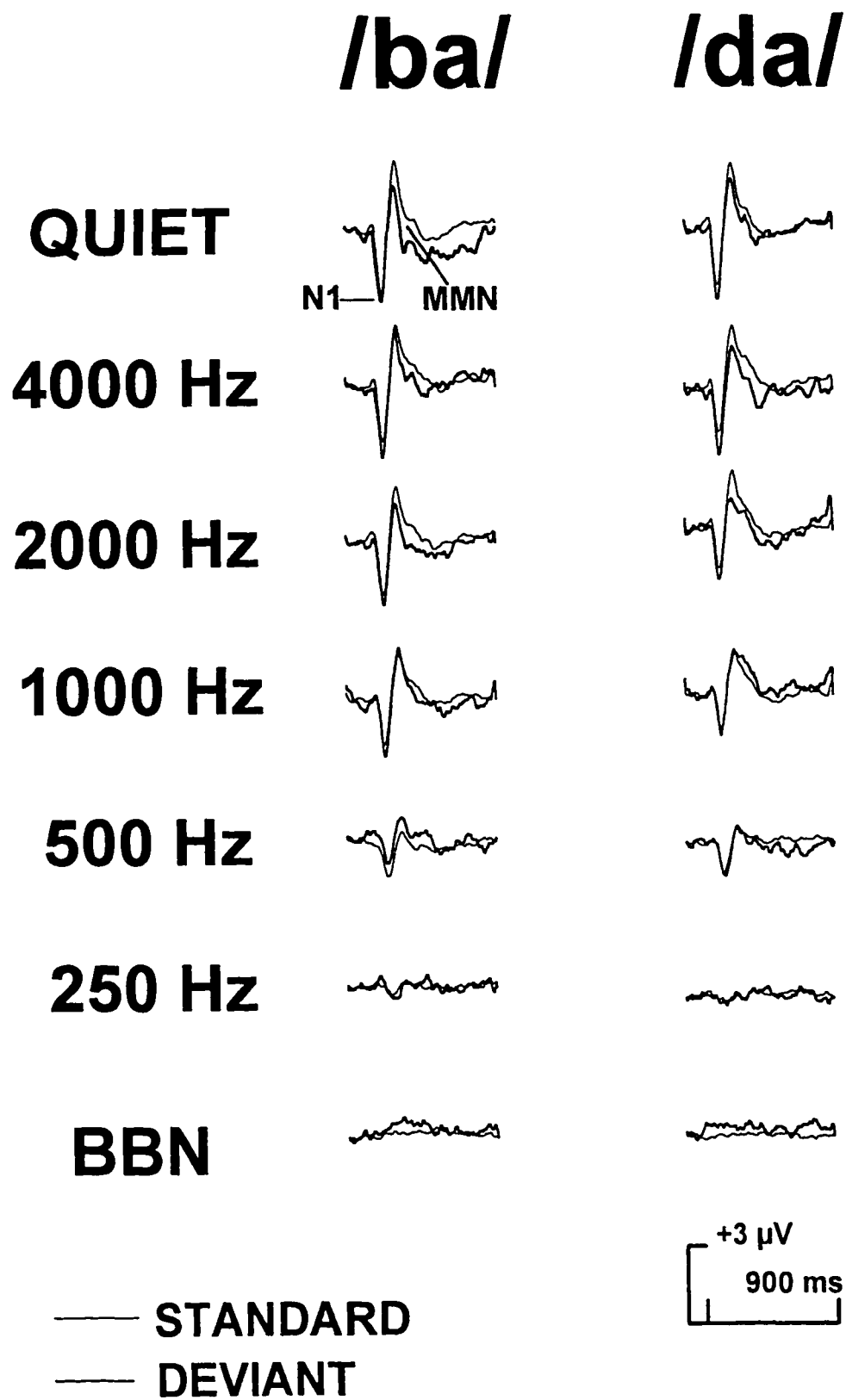


Figure 4

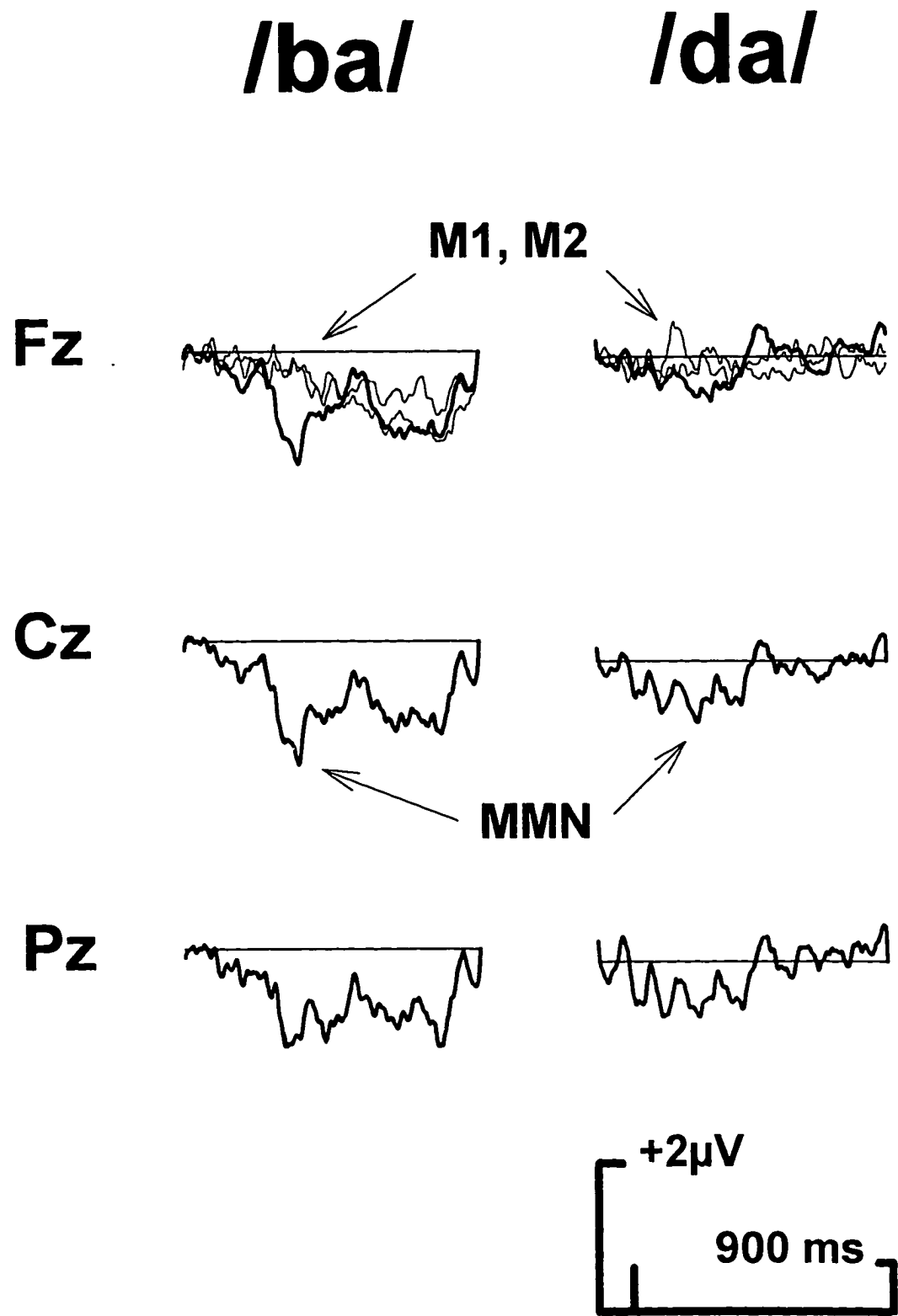


Figure 5

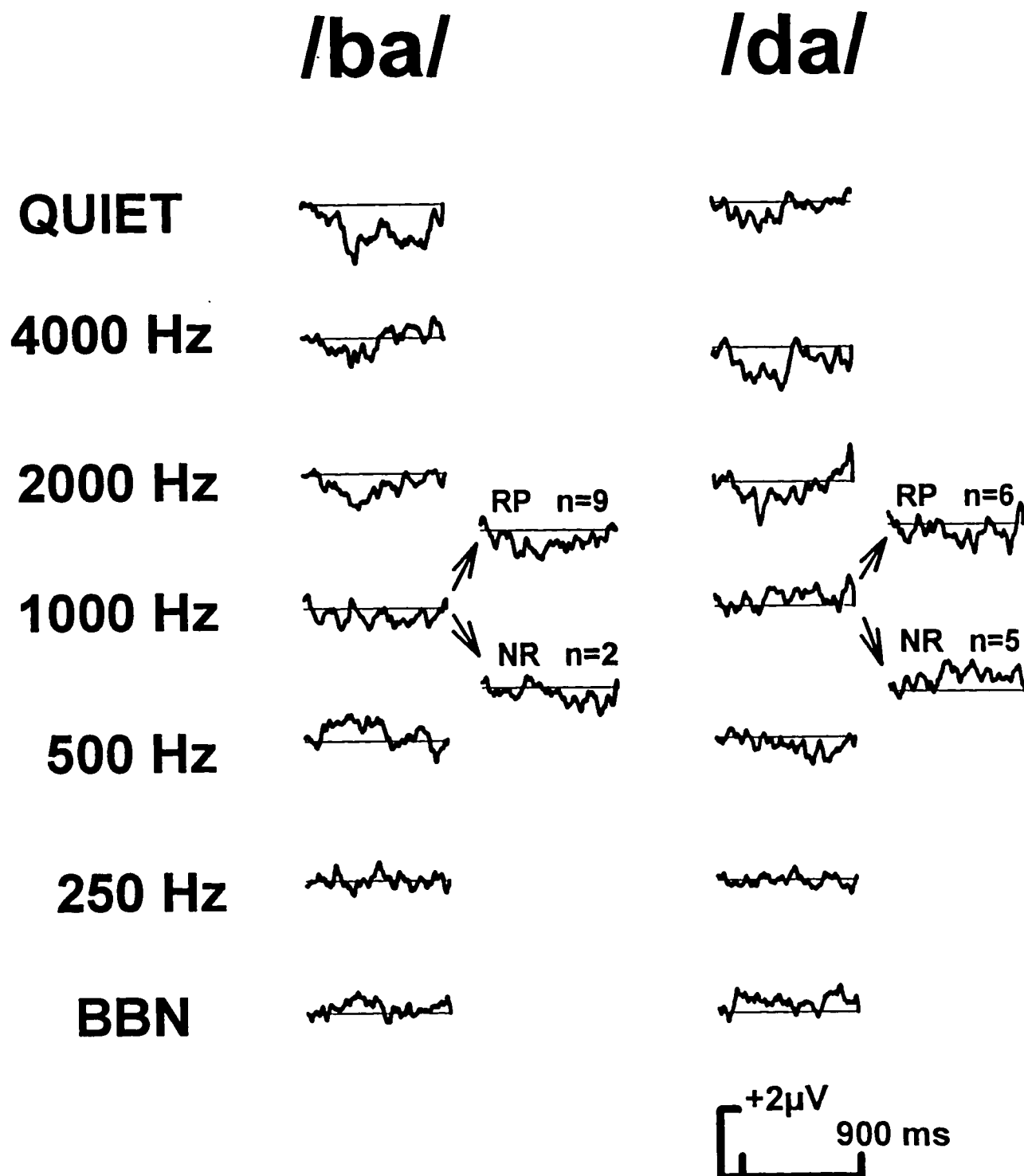


Figure 6

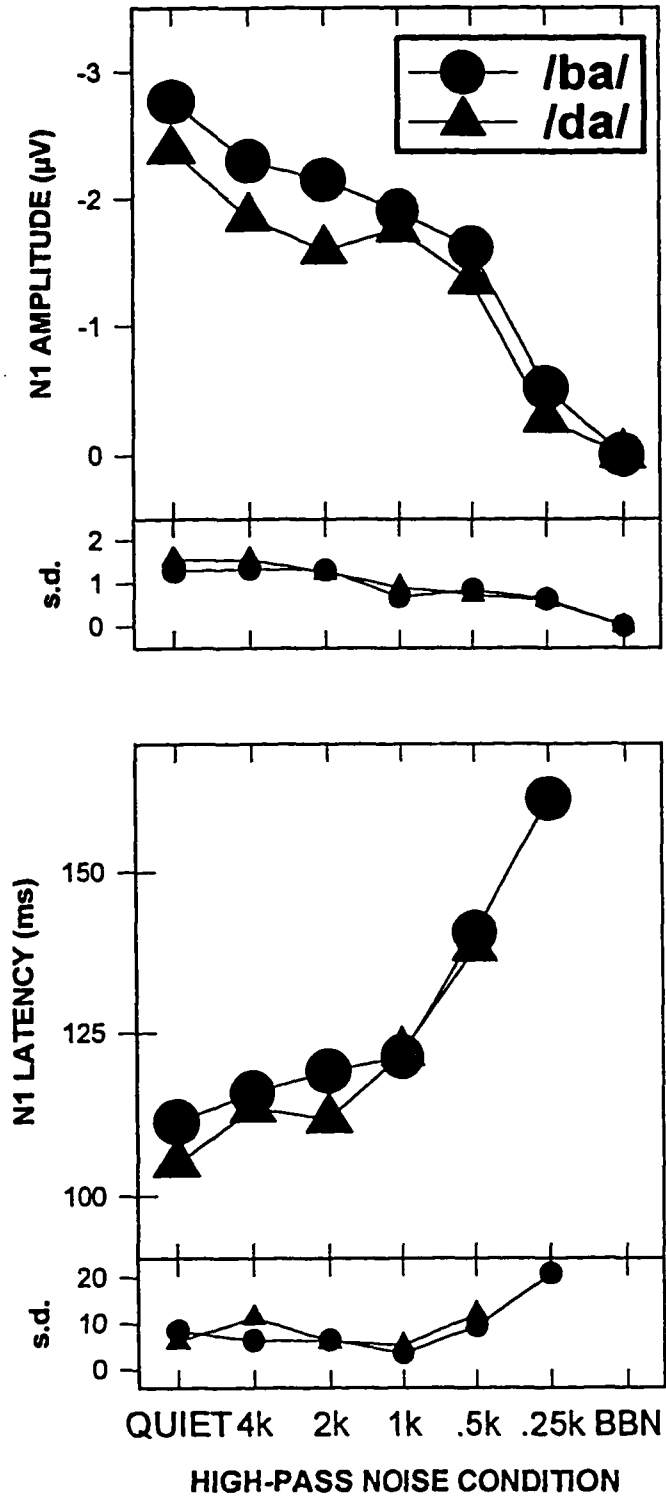


Figure 7

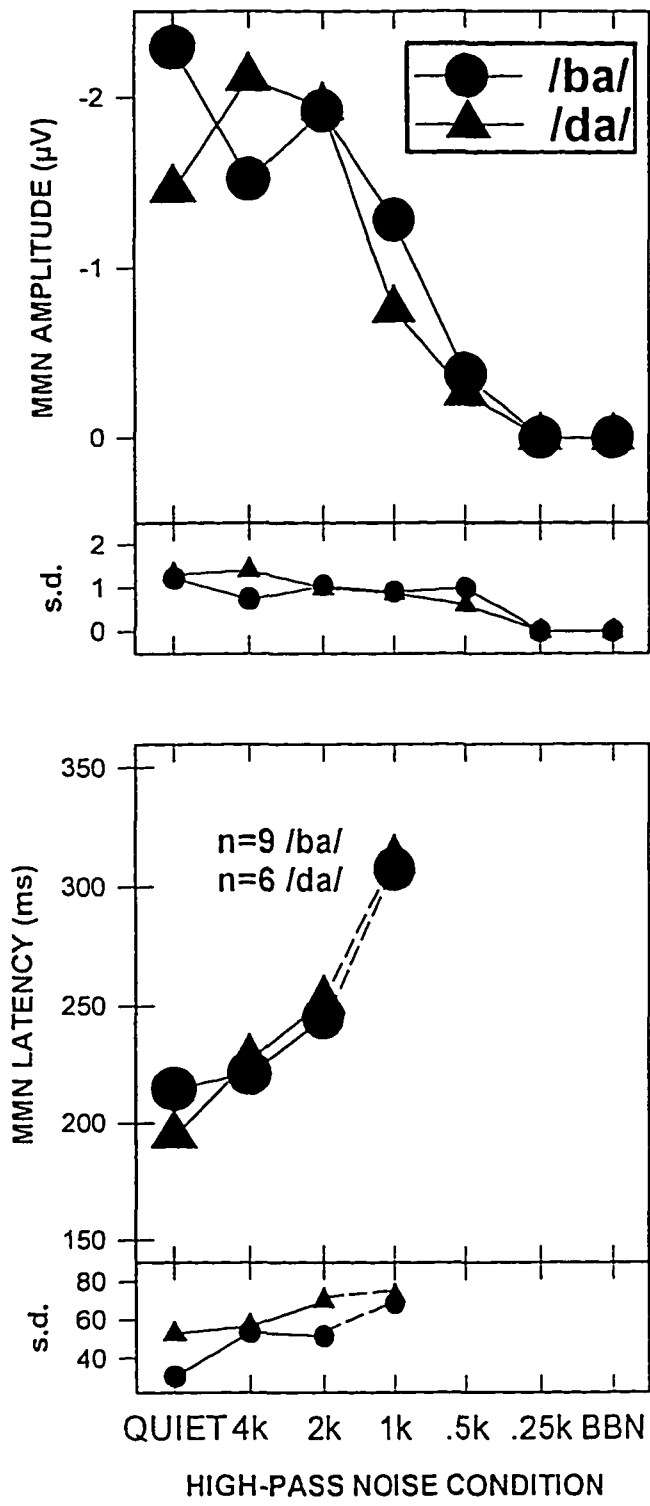


Figure 8

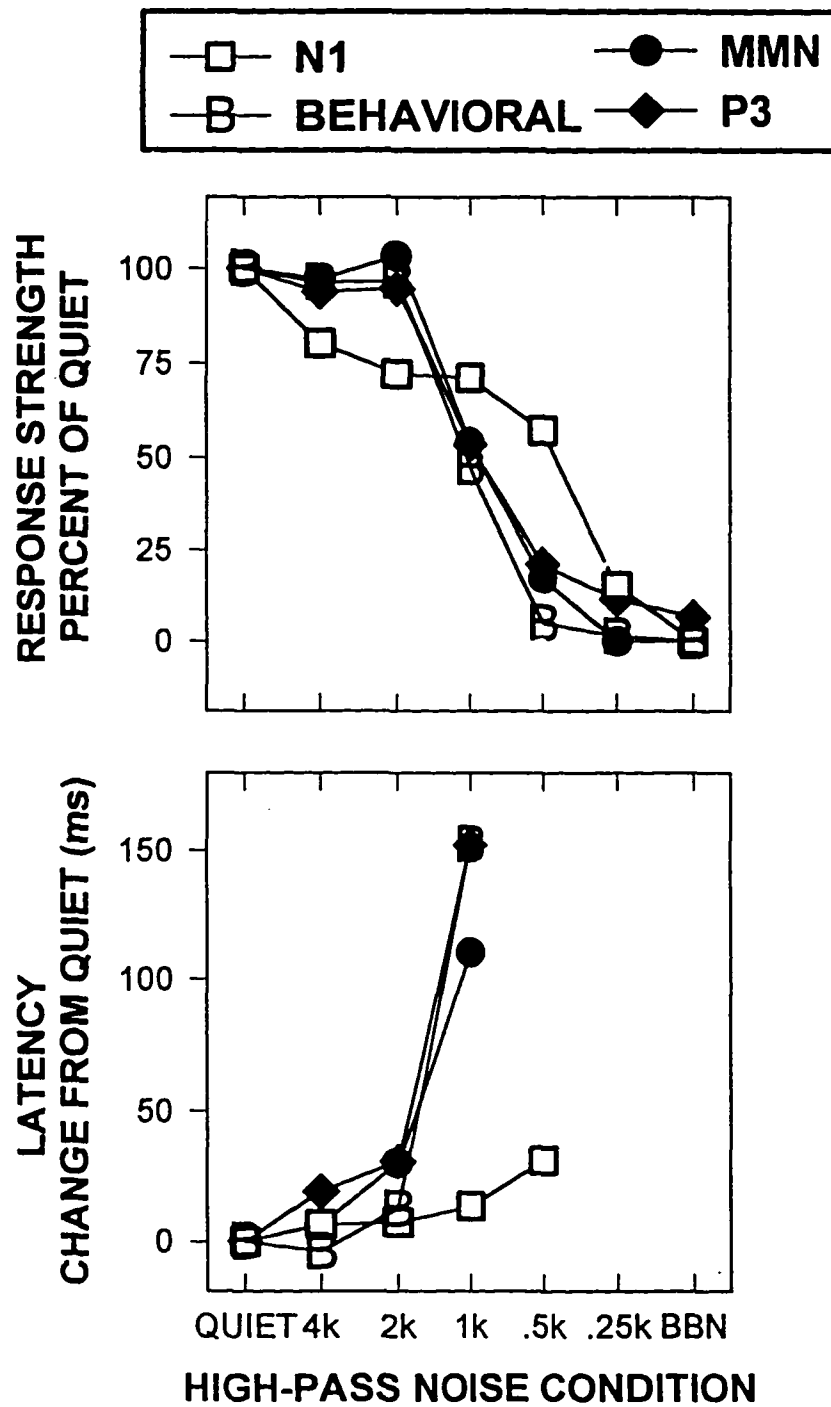


Figure 9

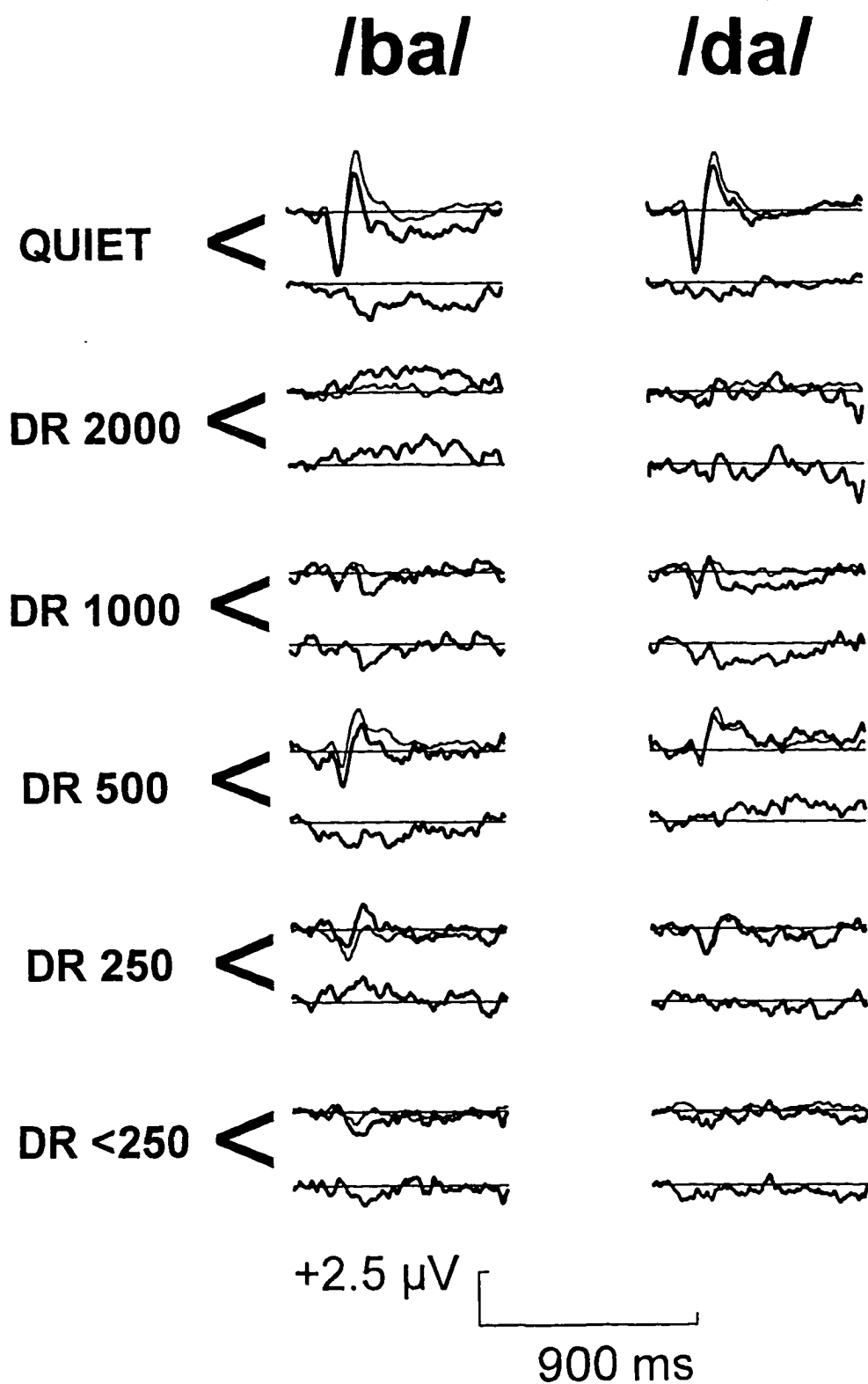
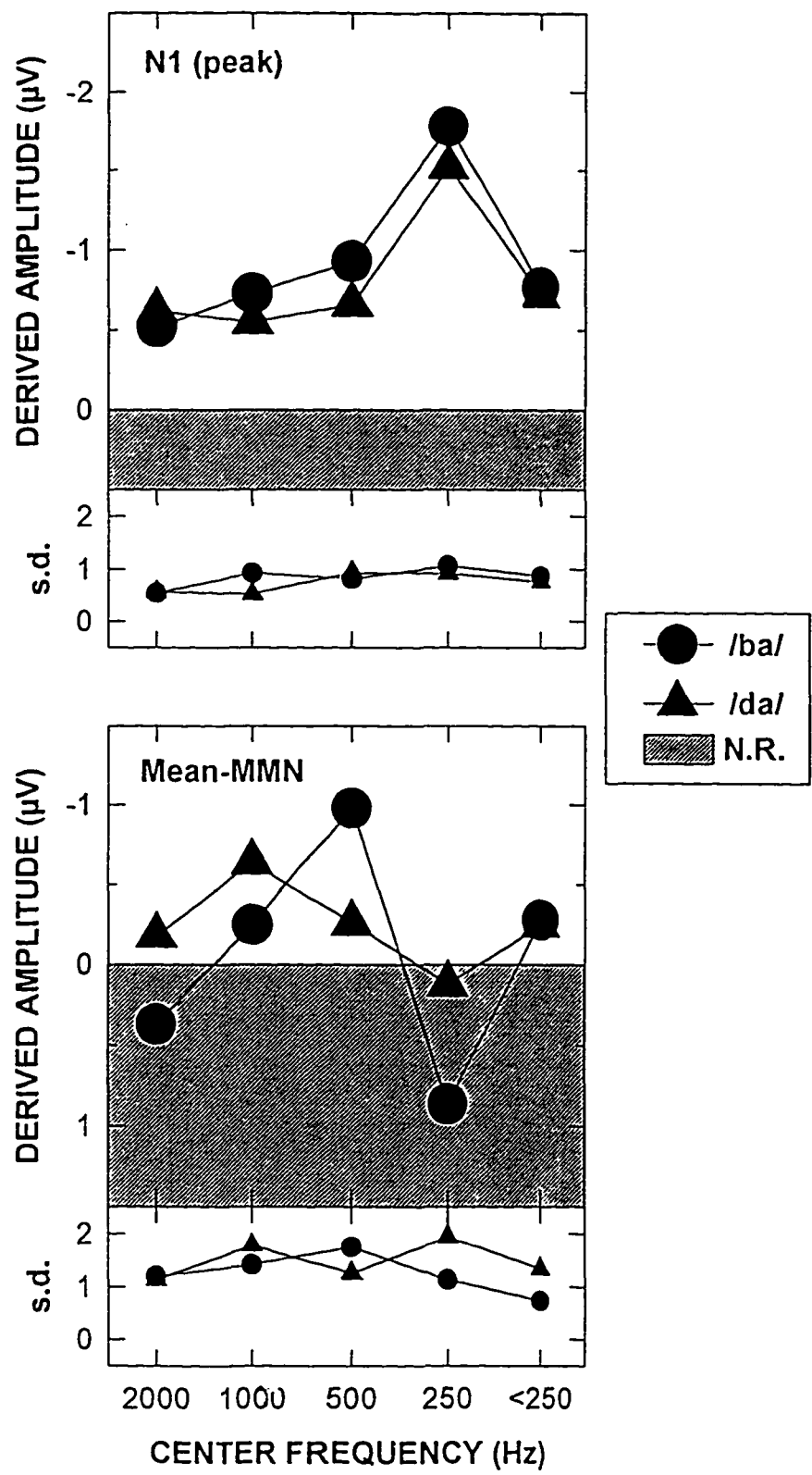


Figure 10



Chapter 5

**The effects of decreased audibility produced by low-pass noise masking
on cortical event-related potentials to speech sounds /ba/ and /da/.**

5A. Abstract

This study investigated the effects of decreased audibility produced by low-pass noise masking on cortical event-related potentials (ERPs) to the speech sounds /ba/ and /da/. The speech sounds were presented at 65- and 80-dB ppe SPL to normal subjects (n=10) while they were engaged in an active condition (pressing a button to deviant sounds), and a passive condition (ignoring the stimuli and reading a book). Broadband masking noise was simultaneously presented at an intensity sufficient to mask the response to the speech sounds, and subsequently low-pass filtered. The conditions were: QUIET (no masking), low-pass noise cutoff frequencies of 250, 500, 1000, 2000, and 4000 Hz, and broadband noise. Behavioral measures of discrimination of the speech sounds (d' , RT) were obtained simultaneously with ERP measures (N1, N2, P3) in the active condition. In the passive condition, the MMN was obtained.

As the cutoff frequency of the low-pass noise masker was raised, ERP latencies increased and amplitudes decreased. The low-pass noise affected N1 differently than the other ERP or behavioral measures, particularly for responses to 80-dB speech stimuli. N1 showed a smaller decrease in amplitude and a smaller increase in latency compared to the other measures. Further, the cutoff frequency where changes first occurred was different for N1. N1 amplitudes showed significant changes when the low-pass noise masker cutoff was raised to 2000 Hz for 65-dB speech sounds, and 4000 Hz for 80-dB speech sounds. N1 latencies showed significant changes when the low-pass noise cutoff was raised to 1000 Hz. In contrast, changes in RT, MMN, N2, and P3 latencies were not significant until the low-pass noise was raised to 1000 Hz for the 65-dB speech sounds, and to 2000 Hz for the 80-dB speech sounds. Significant changes in behavioral d' , MMN, N2, and P3 amplitude did not change until the 2000-Hz low-pass noise condition.

These results indicate that decreased audibility, resulting from the masking, affects N1 in a differential manner compared to MMN, N2, P3 and behavioral measures. N1 indexes the presence of audible stimulus energy, being present when speech sounds are audible, whether or not they are discriminable. MMN indexes stimulus discrimination at a preconscious level. It was present only

when behavioral measures indicated the ability to differentiate the speech sounds. N2 and P3 also were present only when the speech sounds were behaviorally discriminated. N2 and P3 index stimulus discrimination at a conscious level. These cortical ERP in low-pass noise studies provide insight into the changes in brain processes and behavioral performance which occur when audibility is reduced, such as with hearing loss.

5B. Introduction

Few published studies have examined the effects of hearing loss on auditory cortical event-related potentials (ERPs) to speech stimuli (Chapters 3 and 4; Whiting, Martin and Stapells, submitted). Systematic examination of these effects is needed in order to provide insight into changes in neural processing caused by decreased audibility. It is difficult to examine the effects of decreased audibility in individuals with sensorineural hearing loss in a systematic manner, because the effects of sensorineural hearing loss are not limited solely to audibility. Hearing-impaired subjects often have other problems in addition to decreased audibility that are difficult to control for such as decreased frequency or temporal resolution, abnormal loudness growth, etc. (e.g., Fabry and Van Tasell, 1986; Festen and Plomp, 1983; Scharf, 1978; Thibodeau, 1991). As a result, use of filtering or masking of stimuli presented to normal-hearing listeners is often used to control for audibility in a systematic manner (e.g., Dubno and Ahlstrom, 1995; Dubno, Dirks and Ellison, 1989; Fabry and Van Tasell, 1986; Humes, Dirks, Bell and Kincaid, 1987; Miller and Nicely, 1955; Sher and Owens, 1974; Walden, Schwartz, Montgomery and Prosek, 1981; Wang, Reed and Bilger, 1978). ERP results from these normal-hearing listeners may provide information on the brain processes underlying auditory discrimination, and possibly on factors relevant to the poor speech perception ability of many hearing-impaired listeners. Further, findings from these studies may lead to a useful clinical application of the ERPs as objective markers of audibility and auditory discrimination.

Previous studies in this laboratory examined the effects of decreased audibility produced by high-pass or broadband noise masking on ERPs to speech sounds /ba/ and /da/ (Chapters 3 and 4; Whiting, Martin and Stapells, submitted). The high-pass noise masking studies investigated, in normally-hearing subjects, the effects of decreased audibility on ERPs N1, mismatch negativity (MMN), N2 and P3 to speech sounds /ba/ and /da/ (Chapters 3 and 4). High-pass noise masking decreases audibility for spectral regions at and above the masker cutoff frequency. Sensorineural hearing loss typically occurs in high-frequency spectral regions. High-pass noise masking had a

differential effect on N1 *versus* behavioral measures of discrimination [d-prime (d'), reaction time (RT)], P3, N2 and the MMN. N1 was present for all conditions where the speech stimuli were audible, whether or not they were discriminable. P3, N2 and the MMN were present only when behavioral measures of discrimination indicated speech sounds were audible and discriminable. Specifically, when the high-pass noise was lowered below 2000 Hz, P3, N2 and MMN amplitudes decreased and latencies increased significantly, and behavioral measures of discrimination also showed significant changes (Chapters 3 and 4).

Broadband noise (BBN) masking produces threshold elevations for all audiometric frequencies, and simulates, in part, the effects of flat hearing loss. The BBN maskers produced significant decreases in ERP amplitudes and behavioral discriminability (Whiting *et al.*, submitted). These decreases did not occur until speech-to-noise ratios were ≤ 0 dB. N1 remained present even after N2, P3 and behavioral discriminability were absent. In contrast to amplitudes, ERP and behavioral reaction times showed significant decreases at higher (better) speech-to-noise ratios. Significant latency increases occurred when the speech-to-noise ratio was ≤ 20 dB. Significant latency increases occurred with less masking for N1 than for P3 or behavioral reaction time with N2 falling in-between. Total changes, however, were greatest for P3. The study concluded that decreased audibility resulting from broadband noise masking affects the various ERP peaks in a differential manner, and that latencies are more sensitive indicators of broadband masking effects than are amplitudes (Whiting *et al.*, submitted).

The present study was designed to investigate the effects of low-pass noise masking on ERPs N1, MMN, N2 and P3 to speech sounds /ba/ and /da/. Low-pass noise was selected because hearing loss does not always occur in high-frequency spectral regions alone, or just with flat audiometric configurations, but also may also occur only in low-frequency spectral regions. The use of low-pass noise raises thresholds for frequencies at and below the filter cutoff settings, as well as above, due to upward spread of masking (e.g., Dubno and Ahlstrom, 1995). These low-pass noise studies, considered with the high-pass noise studies, provide for a more complete understanding of the effects of decreased audibility for different spectral regions.

5C. Method

Subjects

Ten adults (4 males, 6 females) aged 24 to 40 years (mean = 33 years), with no history of neurological disorder, participated. All subjects had hearing thresholds of 20 dB HL (ANSI, 1989) or better bilaterally, from 250 through 8000 Hz. Additionally, acoustic immittance testing was performed prior to each session in order to rule out changing or abnormal middle-ear status. All subjects had a normal tympanogram and a present ipsilateral acoustic reflex (1000 Hz, 90 dB HL) in their test ear. Subjects were tested over four to five sessions and were paid for their participation.

Stimuli

The /ba/ and /da/ stimuli for these studies were selected because discrimination of place of articulation is typically difficult for hearing-impaired listeners due to the high-frequency content and low intensity of the spectral energy necessary for place discrimination. These are the same stimuli used in our studies of the effects of high-pass noise masking (chapters 3 and 4), and broadband noise masking (Whiting *et al.*, submitted) on cortical ERPs. The stimuli were created by digitizing natural tokens produced by a male talker. The tokens were then processed using linear prediction coefficient (LPC) analysis, and synthesized tokens were regenerated using the LPC polynomial roots (Maiste, Wiens, Hunt, Scherg and Picton, 1995). The tokens were recorded by a Neuroscan STIM system using a 30,000 Hz sampling rate (10,000 Hz anti-aliasing filter, 12 dB/octave slope), edited to 150-ms duration (by eliminating the final portion of the steady-state vowel and windowing the offset of the vowel), and calibrated in peak-to-peak equivalent (ppe) SPL, relative to a 1000-Hz pure tone.

Spectrographic analysis was used to determine the frequencies of the formants and formant transitions for both /ba/ and /da/. The frequencies of the steady state portion of the vowels were: F0 = 108 Hz, F1 = 674 Hz, F2 = 1140 Hz, and F3 = 2350 Hz. The transitions for /ba/ began at 328 Hz for F1, 1071 Hz for F2, and 2298 Hz for F3; the transitions for /da/ began at 362 Hz for F1, 1832 Hz for F2, and 2540 Hz for F3. Burst frequencies were similar for the two speech sounds (1500-4800 Hz for /ba/; 1200-4900 Hz for /da/). Thus, the primary differences between the stimuli are in

the 1000 to 2000 Hz range (see spectrogram in Chapter 3, Figure 1). The stimuli were delivered at a D/A rate of 30,000 Hz (10,000 Hz anti-imaging filter, 12 dB/octave slope), and presented to the right ear of the subjects at 65 and 80 dB ppe SPL.

For the active discrimination conditions, 200 stimuli were presented in a run, which was replicated, yielding a total of 400 stimuli per condition. For passive conditions, 1000 stimuli were presented in a run, which was replicated, yielding a total of 2000 stimuli per condition. The passive sessions require a larger number of sweeps because of the small amplitude and large variability of the MMN (e.g., Kurtzberg, Vaughan, Kreuzer and Fleigler, 1995; Lang, Eerola, Korpihähti, Holopainen, Salo and Aaltonen, 1995; Chapter 4). Stimuli presented as standards (i.e., the more frequently occurring stimulus in the run) had .90 probability of occurrence and stimuli presented as deviants (i.e., the infrequently occurring stimulus within the run) had .10 probability. The onset-to-onset interstimulus interval (ISI) was 1100 ms for the active discrimination sessions, in order to obtain clear N1 and P3 waves (in the QUIET condition). The ISI for the passive sessions was 610 ms in order to improve the signal-to-noise ratio of the recording (by allowing more trials to be recorded), and therefore to obtain a clear MMN (in the QUIET condition). Both speech sounds were presented as standards and deviants in separate runs. Presentation order of the stimuli *within* each run for the passive sessions was not randomized (e.g., Scherg, Vajsaar and Picton, 1987), and the deviant stimulus was presented every 10th trial. In contrast, stimulus presentation order *within* a run for the active discrimination sessions was pseudorandomized, with the provision that there were not two deviants in a row, and the first stimulus could not be a deviant.

The 65-dB ppe SPL intensity was selected because of its similarity to conversational speech levels. The 80-dB ppe SPL intensity was selected because this is a higher intensity and therefore mimics, in part, the effects of amplification. Inclusion of this intensity allows for examination of whether noise-masked stimuli that were inaudible at 65 dB become audible at 80 dB, and whether stimuli not discriminable at the lower intensity become discriminable.

Masks

The speech stimuli were presented in QUIET, and in conditions mixed with ipsilateral masking noise. The masking noise originated from a Coulbourn noise generator (model S81-02), and was fed to a Wavetek Dual Hi/Low filter (model 852) with both channels set to low pass and connected in series (96 dB/octave slope). After filtering, the noise was passed to an active attenuator and fed to a Coulbourn audio mixer-amplifier (model S82-24), where the noise was mixed with the stimulus (either the speech sounds for the ERP testing or the pure tones for behavioral audiological testing). Finally, the noise together with the stimulus was fed to a series of passive attenuators, and then fed to an EAR-3A insert earphone. The level of the broadband noise (BBN) required to fully mask behavioral perception of the 65-dB ppe SPL speech sounds was determined for each subject by the following procedure: The masking level was increased using 10-dB steps until the speech sounds were not heard. The masking level was then decreased by 10 dB, and a bracketing approach initiated using a 1-dB step size. Masked threshold was defined as the level at which the speech sounds were inaudible 50% of the time. The masking noise was then increased by 7 dB above this level to ensure adequate masking of the speech sounds, as the threshold for masking ERPs is often a few dB higher than the threshold for masking perception (Stapells, Picton and Durieux-Smith, 1994). The noise was subsequently low-pass filtered using settings of 4000, 2000, 1000, 500 and 250 Hz. These cutoff settings were selected because they allow us to control for audibility in the frequency regions most important for speech perception, are commonly used in behavioral studies, and were used in our previous high-pass noise masking studies. The same noise intensity was used for both the 65- and 80-dB ppe SPL speech stimuli. The 80-dB stimuli, therefore, were not completely masked. The intensity required to fully mask these 80-dB stimuli would be potentially damaging. The masking noise (unfiltered) ranged from 77.5 to 85.5 dB SPL (mean = 80 dB).

EEG Recording

Seven EEG channels were recorded from electrodes placed at Fz, Cz, Pz, M1, M2, C3M (midway between C3 and M1), and C4M (midway between C4 and M2). The EEG channels were referenced to an electrode at the tip of the nose. This location is less active than other cephalic sites because the nose is on the zero isopotential line for N1 and the MMN due to their generation in the vicinity of the primary auditory cortex (Alho, 1995; Vaughan and Ritter, 1970). An eighth channel to monitor vertical eye movements and eye blinks (EOG) was recorded from electrodes over the right supraorbital ridge of the frontal bone and on the zygomatic bone under the right eye. An electrode placed on the neck served as ground. Electrode impedances were maintained below 5000 Ohms, with differences between electrode pairs not exceeding 2000 Ohms. The seven EEG channels were amplified (gain = 20,000), filtered (0.1 to 100 Hz, 6 dB/octave slope), and digitized (568 Hz per channel, 512 points) using either a 900-ms (active discrimination) or 550-ms (passive condition) analysis time. The analysis time included 100-ms pre-stimulus baseline for the active discrimination conditions, and a 50-ms pre-stimulus baseline for the passive conditions. Amplitude measures were made relative to the prestimulus baselines. The EOG channel was filtered and digitized as above, but the amplifier gain was set to 5000. Single-trial ERP waveforms were saved for offline baseline correction across the sweep duration, digital filtering (30-Hz low-pass filter, 12 dB/octave), artifact rejection (± 100 μ V in any of the channels, and ± 75 μ V in the EOG channel) and averaging. ERPs were averaged separately for each stimulus, and averages were baseline corrected using the pre-stimulus interval. Two replications of each condition were obtained.

Behavioral Measures

Behavioral pure-tone audiograms for 250 to 4000 Hz were obtained in QUIET and in the presence of the noise maskers for all of the subjects using a GS 1701 audiometer.

Measures of reaction time (RT) and percent correct discrimination were obtained simultaneously with the ERP measures using button-press responses to the deviant stimuli in the active conditions. Measures of a subject's median reaction time, number of hit, false alarm, correct rejection and

miss trials were obtained, and criterion-free measures of sensitivity (d') were calculated for each active condition.

Procedure

The experiment consisted of EEG recordings obtained for active and passive conditions, and the audiograms. The experiment was run over four to five sessions, for a total time of approximately 21 hours per subject.

For the active discrimination conditions, subjects were instructed to fixate on a small dot placed approximately one meter in front of them at eye level, to minimize eye blinks, and to press a button as soon as they heard the deviant stimuli. They were advised to place equal weight on the speed and accuracy of their button presses. Subjects were presented with two practice runs in the QUIET condition, composed of 100 stimuli (one run where /ba/ was the deviant sound and one run where /da/ was the deviant sound). Only those subjects attaining accuracy of 90% or better in these practice runs were accepted for the study. Based on this criterion, no subject was rejected. In the passive conditions, subjects were instructed to ignore the stimuli and to concentrate on reading a book of their choice. They were advised to hold the book at an arm's length in order to reduce horizontal eye movement, and to minimize eye blinks.

All testing was performed in a double-walled sound booth (Industrial Acoustics Corporation). Responses to the speech sounds were obtained in QUIET (no masking), in broadband noise, and in 250-, 500-, 1000-, 2000- and 4000-Hz low-pass noise. The conditions were randomized with the exception that one broadband noise condition for a 65-dB speech stimulus was tested first, to ensure adequate masking of the ERPs to the speech sounds. Passive conditions were tested before the active discrimination conditions, as it may be difficult for subjects to ignore stimuli to which they had previously been instructed to attend.

Data Analysis

After offline processing of baseline correction and artifact rejection, the single-trial responses were averaged so that responses to stimuli presented as standards and deviants were grouped separately. Replications were averaged together for each condition. Difference waveforms were

obtained by subtracting responses to the stimuli presented as standards from the responses to the same stimuli presented as deviants for each condition.

Response windows developed in our previous high-pass noise studies (Chapters 3 and 4) were used to aid in response measurement for data from individual subjects. Response windows were 80-200 ms for N1, 200-420 ms for N2, 285-800 ms for P3, and 80-400 ms for the MMN. The onset of the response windows was developed using the grand mean data from the QUIET conditions minus approximately 20% of the peak duration in order to accommodate individual subjects who had responses earlier than the grand mean. The offset of response windows was developed using the grand mean responses from the most difficult conditions where responses were present in the grand mean data (i.e., 250-Hz high-pass noise conditions for both stimulus intensities, and the BBN condition for the 80-dB ppe SPL stimulus intensity), as well as inspection of the data from individual subjects (Chapters 3 and 4). For P3, the offset of the response window was set at the maximum latency of the analysis time (800 ms). Additionally, the noise-masked results from individual subjects in the present experiment were inspected to ensure that the response windows were adequate.

N1 was measured in the waveforms to the stimuli presented as standards at Cz; P3 was measured in the waveforms to the stimuli presented as deviants at Pz for active conditions; N2 was measured in the difference waveforms at Cz for the active conditions; and MMN was measured in the difference waveforms at Cz for the passive conditions. These measurement locations were chosen because they are where the largest amplitudes were seen in the grand mean waveforms in the previous high-pass noise masking studies (Chapters 3 and 4). Measurements were made on the average of the two replicated waveforms for each condition. Peak amplitude measures were determined at the point of largest amplitude within a response window. Latency measures were taken at the center of the peak within the window. In cases where a wave was multi-peaked, both amplitude and latency measures were taken at the point of largest amplitude within the response window. In cases of double peaks of equal amplitude, amplitude was measured at either peak, and latency was measured at the midpoint of the waveform. For P3, latency measures were

obtained after digital low-pass filtering at 5 Hz (12 dB/octave in the frequency domain) to smooth the waveform (Chapter 3; Picton, 1992). In addition to peak amplitude and latency measures, mean amplitude measurements over a 100-ms window were performed for the MMN. These mean-MMN measures were taken over a time period beginning 20 ms past the grand mean N1 latency for each noise condition and lasting 100 ms.

Determination of response presence required the agreement of two experienced, independent judges. The presence of N1 was determined using the waveforms to the stimuli presented as standards. To be considered present, N1 was required to be larger in amplitude at frontocentral electrode sites than at parietal electrode sites. Inversion at the mastoid electrode sites was used to indicate response presence, but lack of inversion was not used to indicate response absence. The presence of N2 or the MMN were determined using the difference waveforms. N2 must be larger in amplitude at midline-central electrode sites. When questionable, the waveforms to the stimuli presented as standards and deviants were compared and larger negativity in the waveforms to the deviant stimuli than to the standard stimuli in the N2 latency window was required for response presence. The same rules apply for the MMN, except that inversion at the mastoids was used to indicate response presence, though lack of inversion alone was not enough to indicate response absence. Mean-MMN measures, by definition, did not involve rating by judges. The presence of P3 was determined using the waveforms to the stimuli presented as deviants. To be considered present, P3 was required to be larger at Pz than at frontocentral electrode sites. When questionable, the waveforms to the stimuli presented as standards and deviants were compared, and larger positivity in the waveforms to the deviant stimuli than to the standard stimuli in the P3 latency window was required for response presence. When judgements were considered questionable using the above rules, the replicability of the waveforms was examined. If the wave was replicable, then it was judged as present. When a wave was judged absent, it was given an amplitude of zero μV .

Statistical Analyses

Three-way repeated measures analyses of variance (ANOVA) as a function of speech stimulus, stimulus intensity and noise condition were carried out on the amplitude and latency data. Additionally, four-way ANOVAs as a function of wave, intensity, stimulus and condition were carried out on normalized amplitude and latency data. The data were normalized by conversion to percent of (d' , amplitude) or change from (RT, latency) the QUIET condition. Main effects and interactions were considered significant if $p < .01$. Greenhouse-Geisser epsilon correction factors (η) were applied to the degrees of freedom, and are reported where appropriate (Greenhouse and Geisser, 1959). Reported probabilities reflect these adjustments. For latency measures, the repeated measures ANOVAs were performed in a manner to maximize the number of conditions in the analysis. This required that some subjects be eliminated (due to missing data). Conditions were eliminated, however, if fewer than five subjects remained. In this case, two-way ANOVAs were carried out on the data from the 80-dB conditions. Neuman-Keuls *post-hoc* measures were performed when significant main effects or interactions were obtained. The *post-hoc* results were considered significant if $p < .05$. Pearson product-moment correlation coefficients were calculated between the behavioral measures of discrimination and reaction time and N1, N2, MMN and P3 latency and amplitude. Correlation results were considered significant if $p < .01$.

5D. Results

Behavioral Results

Masked Audiograms

Behavioral masked and nonmasked pure-tone audiograms are displayed in Figure 1 (see Figure 1). Shown are the mean threshold data in dB SPL for the 10 subjects (top), and the corresponding standard deviations (bottom). The masking noise produced moderate threshold elevations at and below the filter cutoff, and small (5-10 dB) threshold elevations above the filter cutoff. Across all cutoff frequencies, the low-pass noise increased thresholds by an average of 49

dB one octave below the low-pass cutoff, 44 dB at the low-pass cutoff, and by 10 dB one octave above the cutoff.

Behavioral Measures (d' , RT)

Figure 2 (top) shows the behavioral d' results as a function of noise masking condition calculated from button-press responses to deviant stimuli that were obtained in the active discrimination condition (see Figure 2). Statistical analyses of the data indicate a main effect of intensity [$F(1,9) = 31.98$; $p < .001$], whereby d' scores were higher in response to 80-dB stimuli than to 65-dB stimuli, even in the QUIET condition. There is a main effect of low-pass noise condition [$F(6,54) = 299.49$; $p < .001$; $\eta^2 = .2962$], whereby discriminability decreases as the low-pass noise cutoff is raised. *Post-hoc* testing indicates that discriminability does not change significantly until the noise cutoff frequency is raised to 2000 Hz. With 2000-Hz low-pass noise, discriminability drops sharply, and continues to drop to near-zero levels as the low-pass noise cutoff is raised. There are significant intensity $\times$ stimulus [$F(1,9) = 10.87$; $p = .009$] and intensity $\times$ condition [$F(6,54) = 4.05$; $p = .004$; $\eta^2 = .3411$] interactions. *Post-hoc* testing of the intensity $\times$ stimulus interaction indicates that, across all conditions, d' scores to /ba/ are smaller than are those to /da/ at 65 dB, but not at 80 dB. *Post-hoc* testing of the intensity $\times$ condition interaction indicates that noise condition has a differential effect on the responses to the 65- versus the 80-dB speech sounds. The decrease in d' scores as the low-pass noise cutoff is raised begins with the 1000-Hz low-pass condition for the 65-dB speech sounds, whereas the decrease begins only with the 2000-Hz low-pass condition for the 80-dB speech sounds. In other words, the effects of the low-pass noise masking are greater on the responses to the 65-dB stimuli. There is a trend toward an intensity $\times$ stimulus $\times$ condition interaction [$F(6,54) = 4.27$; $p = .013$; $\eta^2 = .5070$]. Examination of the data suggests that changes in d' scores in response to /ba/ presented at 65 dB begin with the 500-Hz low-pass noise condition, whereas changes for /da/ begin with the 1000-Hz low-pass noise condition. Changes in d' scores in response to the 80-dB stimuli do not begin until the 2000-Hz low-pass noise condition.

The lower panel of Figure 2 shows the reaction time (RT) measures to the deviant stimuli. For both behavioral and ERP measures of latency, only those conditions where at least five of the subjects had responses are plotted (RTs associated with a d' score ≥ 1.0 ; ERPs judged as present). There is a trend for a main effect of intensity [$F(1,9) = 5.57$; $p = .043$], whereby RTs to 65-dB stimuli are longer than are RTs to 80-dB stimuli. There is also a trend for a main effect of speech stimulus [$F(1,9) = 7.87$; $p = .021$], whereby RTs to /ba/ are longer than are those to /da/. No main effect for condition is present [$F(3,27) = 2.16$; $p = .167$; $\eta^2 = .4375$], probably due to the conditions removed as a result of missing data. Therefore, results for 65 and 80 dB were analyzed separately (see next paragraph). There is a significant intensity x condition interaction [$F(3,27) = 7.23$; $p = .008$; $\eta^2 = .5567$]. *Post-hoc* testing indicates that reaction time increases significantly when the masking cutoff for the 65-dB speech sounds is raised to 1000 Hz, whereas reaction times for the 80-dB stimuli did not show significant increases when the masking cutoff was raised to 1000 Hz. There were not enough responses in the 2000-Hz low-pass noise condition for 65-dB speech sounds, however, to allow a comparison at 2000 Hz. There is a trend toward a stimulus x condition interaction [$F(3,27) = 4.58$; $p = .021$; $\eta^2 = .7271$]. Reaction times are longer for /ba/ than for /da/, even in the QUIET condition, and in general the differences become greater as the noise cutoff frequency is raised.

In contrast to d' score, there is no main effect of low-pass noise condition [$F(3,27) = 2.16$; $p = .167$; $\eta^2 = .4375$] on RT due to missing data and the resulting smaller number of subjects included in the analysis. Therefore, data in response to the 80-dB stimuli were analyzed separately from data in response to the 65-dB stimuli (allowing for statistical analysis of more low-pass cutoff conditions than for the 65- and 80-dB data combined, due to missing data at 2000 Hz for the 65 dB intensity). These separate analyses indicate a significant effect of low-pass noise masking condition [$F(4,24) = 22.73$; $p < .001$; $\eta^2 = .3363$] for 80-dB stimuli. *Post-hoc* testing indicates that reaction times increase significantly when the low-pass noise masking cutoff is raised to 2000 Hz. There is also a significant effect of speech stimulus [$F(1,6) = 19.91$; $p = .004$], with reaction times to /da/ being shorter than those to /ba/.

Event-Related Potentials**Active Discrimination Condition**

The grand mean waveforms to /ba/ and /da/ from all 10 subjects recorded to the 65-dB stimuli in the active discrimination condition are shown as a function of noise condition in Figure 3 (see Figure 3). Responses recorded from Cz are displayed for N1 and responses recorded from Pz are displayed for P3 because the grand mean data showed responses were largest in amplitude at these electrode sites. N1 is clearly present in the responses to stimuli presented as standards in the QUIET, 250-, 500-, and 1000-Hz low-pass noise conditions and absent in the 4000-Hz and broadband noise conditions. The amplitude of N1 decreases and its latency increases as the low-pass cutoff frequency is raised. P3 is clearly present in the QUIET, 250-, 500-, and 1000-Hz conditions, and is clearly absent in the 4000-Hz through broadband noise conditions. The amplitude of P3 decreases and latency increases as the low-pass noise cutoff is raised to 1000 Hz, and P3 disappears as the low-pass noise cutoff is raised further.

Figure 4 displays N2 in the difference waveforms recorded at Cz in the 65-dB active discrimination condition (see Figure 4). Responses for /ba/ and /da/ are shown separately as a function of noise masking conditions. N2 amplitudes decrease and latencies increase as the low-pass noise cutoff is raised to 1000 Hz. N2 disappears when the masker cutoff frequency is raised further.

Figure 5 displays the grand mean ERPs in response to /ba/ and /da/ presented at 80 dB in the active discrimination condition (see Figure 5). N1 is present in QUIET and in all of the noise masking conditions. Its amplitude decreases and latency increases as the low-pass noise cutoff is raised. P3 is clearly present in the QUIET through 2000-Hz low-pass noise conditions, but is absent in the 4000-Hz and broadband noise conditions.

Figure 6 displays the grand mean difference waveforms at Cz in the active discrimination condition in response to 80-dB stimuli (see Figure 6). N2 is clearly present in the QUIET, 250-, 500-, 1000-, and 2000-Hz conditions. Its amplitude decreases and latency increases as the low-pass noise masker cutoff is raised to 2000 Hz. N2 is absent in the broadband noise condition.

N1. Figure 7 (see Figure 7) displays the effects of the noise condition on N1 amplitude (top) and latency (bottom). There is a main effect of intensity [$F(1,9) = 18.32$; $p = .002$], whereby N1 amplitudes in response to 80-dB speech sounds are larger than those to 65-dB speech sounds. There is a main effect of low-pass noise condition [$F(6,54) = 34.34$; $p < .001$; $\eta^2 = .3176$]. There is also an interaction between stimulus intensity and low-pass noise condition [$F(6,24) = 8.00$; $p = .001$; $\eta^2 = .4492$]. *Post-hoc* analyses indicate that N1 amplitudes in response to 65-dB speech sounds decrease when the low-pass noise cutoff is raised, with changes reaching significance only when the low-pass noise cutoff is raised to 2000 Hz and higher. In contrast, N1 amplitudes in response to speech sounds presented at 80 dB are significantly reduced only when the low-pass noise cutoff is raised to 4000 Hz and above. There is no main effect of speech stimulus on N1 amplitude [$F(1,9) = 0.03$; $p = .872$].

There are significant main effects of intensity [$F(1,4) = 31.96$; $p = .005$], stimulus [$F(1,4) = 26.31$; $p = .007$] and noise condition [$F(4,16) = 78.91$; $p < .001$; $\eta^2 = .3800$] on N1 latency. Responses to 80-dB speech sounds are earlier in latency than are those to 65-dB speech sounds, and responses to /da/ are earlier than those to /ba/. Both of these effects are seen even in the QUIET condition. *Post-hoc* analyses indicate that N1 latencies are significantly increased when the low-pass noise cutoff is raised to 1000 Hz. An ANOVA on only the responses to the 80-dB speech sounds also shows significant main effects of stimulus [$F(1,8) = 16.03$; $p = .004$], with latencies for /da/ being earlier than those for /ba/. Additionally, there is a main effect of condition [$F(5,40) = 63.76$; $p < .001$; $\eta^2 = .4677$], with significant latency increases occurring when the low-pass noise is raised to 1000 Hz and above.

N2. The effects of noise condition on N2 amplitude (top) and latency (bottom) are displayed in Figure 8 (see Figure 8). There is a main effect of intensity [$F(1,9) = 11.94$; $p = .007$], whereby N2 amplitudes are larger in response to 80-dB speech sounds than to 65-dB speech sounds. As the low-pass noise cutoff is raised, N2 amplitudes drop, indicated by a significant main effect of

condition [$F(6,54) = 28.17$; $p < .001$; $\eta^2 = .2687$]. These changes are significant when the noise cutoff is raised to 2000 Hz and above. There is no main effect of speech stimulus [$F(1,9) = 0.01$; $p = .924$].

N2 latencies were longer in response to /ba/ than to /da/ [$F(1,9) = 72.00$; $p < .001$], even in the QUIET condition. There was a trend for a significant effect of noise condition [$F(3,27) = 6.42$; $p = .012$; $\eta^2 = .5713$]. Examination of the data suggest that this is due to longer latencies when the noise cutoff is raised to 1000 Hz. There was no main effect of stimulus intensity [$F(1,9) = 0.51$; $p = .495$]. When data for responses to the 80-dB stimuli are examined alone, there is a significant main effect of low-pass noise condition [$F(4,24) = 17.61$; $p < .001$; $\eta^2 = .5438$]. *Post-hoc* testing indicates that N2 latencies increase significantly when the noise cutoff is raised to 2000 Hz.

P3. The effects of noise condition on P3 amplitude (top) and latency (bottom) are displayed in Figure 9 (see Figure 9). The different symbols indicate P3 amplitude and latency data for all trials, regardless of whether subjects' behavioral response to the deviant stimulus was correct or incorrect (P3-all). The line types (dotted and solid) indicate P3 amplitude and latency data for only those ERPs trials associated with correct behavioral responses (P3-hits). As the low-pass noise cutoff is raised, P3 amplitudes decrease [$F(6,54) = 41.73$; $p < .001$; $\eta^2 = .3254$]. *Post-hoc* analyses indicate that the decrease in amplitude is significant when the noise cutoff is raised to 2000 Hz and above. There is a trend for P3 amplitudes to /da/ to be larger than to /ba/ [$F(1,9) = 5.43$; $p = .045$], even in the QUIET condition. There is no main effect of stimulus intensity [$F(1,9) = 4.19$; $p = .071$].

P3 latencies increase as the low-pass noise cutoff is raised [$F(3,27) = 9.71$; $p = .003$; $\eta^2 = .5351$]. These increases, however, are not significant until the noise cutoff is raised to 1000 Hz and above. There is no main effect of stimulus intensity [$F(1,9) = 3.90$; $p = .080$]. There is a trend for an intensity x condition interaction [$F(3,27) = 3.87$; $p = .044$; $\eta^2 = .6257$]. Examination of the data indicates that the latency changes begin at the 1000-Hz noise cutoff for 65 dB, but that changes occur at higher noise cutoff frequencies for 80-dB stimuli. As a result, a two-way ANOVA was performed on the data from the 80-dB condition. Results indicate a significant effect of noise

condition for the responses to 80-dB stimuli [$F(4,24) = 17.12$; $p < .001$; $\eta^2 = .5323$] that is first significant in the 2000-Hz low-pass noise condition.

The P3 data associated with correct button-press responses (P3-hits) were also examined. There is a trend for amplitudes to be larger in response to 80-dB stimuli than to 65-dB stimuli [$F(1,9) = 9.18$; $p = .014$]. There is also a trend toward larger amplitudes in response to /da/ than to /ba/ [$F(1,9) = 7.26$; $p = .025$]. As the low-pass noise masker cutoff is raised, P3-hits amplitudes drop, resulting in a significant main effect of noise condition [$F(6,54) = 39.96$; $p < .001$; $\eta^2 = .3489$]. There is a significant interaction between intensity and noise condition [$F(6,54) = 7.16$; $p = .006$; $\eta^2 = .3259$], whereby amplitude changes for responses to the 65-dB stimuli are first significant when the noise cutoff is raised to 2000 Hz, but for responses to the 80-dB stimuli, amplitude changes are first significant when the noise cutoff is raised to 4000 Hz and above. There is a trend for an intensity x stimulus x condition interaction [$F(6,54) = 3.31$; $p = .036$; $\eta^2 = .4871$], whereby significant amplitude decreases occur beginning with the 2000-Hz low-pass cutoff except for P3-hits responses to /da/ presented at 80 dB, where the amplitude change does not reach significance until the 4000-Hz low-pass noise.

For those P3 latencies associated with correct button-press responses, there was a significant main effect of condition [$F(3,27) = 6.84$; $p = .005$; $\eta^2 = .7162$], such that latencies increased significantly when the low-pass noise was raised to 1000 Hz. When only the data for the responses to the 80-dB stimuli are examined, the significant main effect of noise condition remains [$F(4,24) = 10.82$; $p = .003$], but does not become significant until the 2000-Hz low-pass noise condition.

An ANOVA was performed directly comparing results for P3 amplitude (P3-all) with results for P3 amplitude associated with correct button-press responses (P3-hits). There is a significant measure x stimulus intensity x low-pass noise condition interaction [$F(6,54) = 9.52$; $p = .003$; $\eta^2 = .2833$]. Amplitudes decrease significantly when the low-pass noise is raised to 2000 Hz, except for P3-all to the 65-dB speech stimuli, where amplitude decreases begin with the 1000-Hz low-pass

noise condition. Comparison of P3 latency (P3-all) with P3 latencies associated with correct button-press responses (P3-hits) did not reveal any significant interactions.

Passive Condition

Figure 10 shows grand mean waveforms recorded in response to the 65-dB stimuli presented as standards and as deviants in the passive condition (see Figure 10). Responses recorded from Cz are displayed because amplitudes were largest at this electrode site in most of the grand mean waveforms. N1 appears to be present in at least the QUIET through 1000-Hz low-pass noise conditions. Changes in N1 as a function of noise masking condition were not measured in the passive condition. Due to the rapid stimulus presentation rate, the generators of N1 were likely refractory in many subjects (e.g., Davis, 1976; Näätänen and Picton, 1987). As a result of this, and perhaps some temporal overlapping, N1 was not always negative in voltage (relative to the prestimulus baseline), and was often difficult to identify. The MMN, seen by an increased negativity in response to stimuli presented as deviants, is clearly present in the QUIET through 1000-Hz low-pass noise masking conditions. The MMN is better seen in difference waveforms.

Figure 11 displays the mismatch negativity in grand mean difference waveforms, recorded from Cz in the passive condition at 65 dB (see Figure 11). The MMN appears to be present in the QUIET through at least the 1000-Hz conditions for /ba/ and /da/, and questionably present in the 2000-Hz low-pass noise condition for both speech sounds. The MMN appears to be absent in 4000-Hz low-pass noise condition. It is clearly absent in the broadband noise conditions, as indicated by no activity below the pre-stimulus baseline (i.e., no negativity). The MMN increased in latency and decreased in amplitude as the low-pass noise masker cutoff was raised.

Figure 12 displays the grand mean waveforms recorded in response to the 80-dB stimuli presented as standards and as deviants in the passive condition (see Figure 12). N1 was clearly present in all of the conditions. The MMN, indicated by increased negativity in responses to deviant stimuli, is clearly present in the QUIET through 2000-Hz masking conditions, and absent in the 4000-Hz low-pass noise and broadband noise conditions.

Figure 13 displays the mismatch negativity in the grand mean difference waveforms recorded at Cz in the 80-dB passive condition (see Figure 13). The MMN is clearly present in the QUIET through 1000-Hz low-pass noise masking conditions, and clearly absent in the 4000-Hz and broadband noise conditions. MMN amplitudes decrease and latencies increase as the low-pass noise masker is raised.

MMN. Figure 14 (see Figure 14) displays the effects of low-pass noise conditions on MMN peak amplitudes (top) and latencies (bottom). MMN peak amplitude decreases as the low-pass noise cutoff is raised [$F(6,54) = 36.03$; $p < .001$], beginning with the 2000-Hz low-pass condition. There are no significant main effects of speech stimulus [$F(1,9) = 2.40$; $p = .156$] or stimulus intensity [$F(1,9) = 4.59$; $p = .061$].

MMN latency increases as the low-pass noise cutoff is raised [$F(3,21) = 10.26$; $p = .003$; $\eta^2 = .5987$]. These changes are first significant when the noise cutoff is raised to 1000 Hz and above. There is also a significant effect of speech stimulus [$F(1,7) = 14.60$; $p = .007$], with responses to /da/ having shorter latency than those to /ba/, even in the QUIET condition. There is no significant main effect of stimulus intensity [$F(1,7) = 3.15$; $p = .119$]. Analysis of the 80-dB results alone also indicates that MMN latency increases significantly when the noise cutoff is raised to 1000 Hz [$F(4,28) = 8.92$; $p = .006$; $\eta^2 = .4131$]. Additionally, there is a trend for latencies to in response to /da/ to be earlier compared to responses to /ba/ [$F(1,7) = 6.25$; $p = .041$].

Table 1 displays mean-MMN amplitude over a 100-ms window as a function of speech stimulus, stimulus intensity and low-pass noise condition (see Table 1). There is a significant main effect of low-pass noise condition on MMN-mean measures [$F(6,54) = 8.41$; $p < .001$; $\eta^2 = .4756$], which was first significant for the 2000-Hz low-pass noise condition. There are no significant main effect of stimulus intensity [$F(1,9) = 1.92$; $p = .200$] or speech stimulus [$F(1,9) = 0.54$; $p = .481$].

Comparison of ERP and Behavioral Measures

Figure 15 (see Figure 15) summarizes the results of the study for behavioral measures (d' , RT) and for ERP measures (N1, MMN and P3). Data are expressed in terms of response strength (percent of QUIET condition) or latency change (millisecond increase from the QUIET condition).

The data in the figure are collapsed across /ba/ and /da/, as there were few interactions involving speech stimulus. A 4-way repeated measures ANOVA on the normalized amplitude data indicates complex changes, with a significant 4-way interaction [measure x intensity x stimulus x condition interaction: $F(24,216) = 2.66$; $p < .001$]. Results are more easily interpreted by breaking down the interaction into its component parts. First, *post-hoc* analysis of a significant measure x condition interaction [$F(24,216) = 2.18$; $p = .002$] reveals a significant decrease in response strength occurs at the 2000-Hz low-pass noise condition for all measures. For N1, however, the effect of the noise masking on response strength is less than for the other measures, especially for 80-dB stimuli. In the 1000-Hz low-pass noise condition, d' shows a significantly greater decrease compared to MMN. There are no significant differences between any of the other measures at the 1000-Hz low-pass noise cutoff. In the 2000-Hz low-pass noise condition, the decrease in d' is significantly greater than all of the ERPs. Also, in the 2000-Hz low-pass noise condition, the MMN shows less of a decrease from the QUIET condition than does P3, and N1 shows a smaller decrease than does N2 (N2 is not shown in Figure 15). There is a significant intensity x condition interaction [$F(6,54) = 6.26$; $p < .001$]. Decreases in response strength with noise condition are greater for responses to the 65-dB stimuli than to the 80-dB stimuli for low-pass noise conditions above 1000 Hz. Finally, the measure x intensity x stimulus x condition interaction appears to be due primarily to N1 showing smaller decreases than the other measures in the 4000-Hz low-pass noise condition for the 80 dB intensity, particularly for responses to /ba/ (not shown in Figure 15 because data for the two speech sounds are pooled).

For latency change from the QUIET condition, the 4-way repeated measures ANOVA indicates a significant measure x condition interaction [$F(12,72) = 2.73$; $p = .004$]. For the 1000-Hz high-pass noise condition, P3 shows significantly larger latency increases than all measures except for N2 (not shown in Figure 15). There is a trend toward a significant intensity x condition interaction [$F(3,18) = 3.67$; $p = .03$], whereby latency change from the QUIET condition as a result of noise masking is larger for responses to the 65-dB stimuli, beginning with the 1000-Hz low-pass noise condition. The significant measure x stimulus x condition interaction [$F(12,72) = 3.85$; $p < .001$]

appears to be due to a larger change from the QUIET condition for P3 and N2 compared to the other waves, particularly for higher low-pass noise conditions, and in response to /ba/ (note: data for the two speech stimuli are pooled in Figure 15, and N2 is not shown).

From Figure 15, it is clear that the low-pass noise affects N1 differently than the other measures. This is particularly evident in the latency-change data. For example, N1 is present through the 2000-Hz low-pass noise condition for the responses to 65-dB speech sounds, and is present through the 4000-Hz low-pass noise conditions for the responses to 80-dB speech sounds. In contrast, behavioral measures, MMN, N2 and P3 are present only through the 1000-Hz low-pass noise condition for the 65-dB speech sounds, and through the 2000-Hz low-pass noise conditions for the 80-dB speech sounds. The amount of latency change from the QUIET condition is smaller for N1 than for the other measures. P3 shows the greatest latency change, N2, MMN and RT show intermediate changes, and N1 shows the smallest changes in latency from the QUIET condition as the low-pass noise masker is raised. In terms of changes in response strength, there is little difference in response strength across the various measures as the low-pass noise cutoff was raised for 65-dB speech sounds. For the 80-dB speech sounds, however, N1 shows a smaller decrease in response strength than do the other measures as the low-pass noise cutoff was raised above 1000 Hz.

The relationships between the ERP and behavioral measures of discrimination were examined using Pearson product-moment correlations (see Table 2). Correlations were completed in two ways: First, including all of the data; and second, in order to eliminate the RT scores reflecting guessing by including only those RTs with a corresponding d' score of 1.0 or better. Eliminating the RT data with low d' scores, however, did not result in better correlations. Table 2, therefore, shows only the correlations completed using all data.

Behavioral d' scores show a strong relationship to all of the ERP amplitude measures. However, for ERP latencies, behavioral d' scores show a strong relationship only for N1. The correlations between MMN, N2 and P3 latency and d' scores were weak, with only the correlation with P3 attaining significance (but accounting only for about 6% of total variance). The correlations

between RT and ERP latency were strong except for the correlation with MMN latency, which was not statistically significant. The correlations between RT and ERP amplitude show a progressive relationship, whereby earlier peaks (N1, MMN) showed small, nonsignificant correlations, and later peaks (N2, P3) showed moderate correlations.

5E. Discussion

The low-pass noise maskers resulted in decreased audibility in specific spectral regions, similar to that seen with moderate low-frequency hearing losses. As the noise cutoff frequency was raised, the portion of the audiogram showing decreased audibility changed systematically from including only low-frequency regions, to low-, mid- and high-frequency regions. This pattern is different from that obtained with high-pass noise masking (Chapters 3 and 4). High-pass noise masking resulted in decreased audibility which changed systematically from including high-frequency regions, to high-, mid-, and low-frequency regions. The low-pass noise masking resulted in small threshold elevations even above the masker cutoff frequency, perhaps due to upward spread of masking (Egan and Hake, 1950). This upward spread of masking may thus result in a different *effective* cutoff frequency for low-pass noise masking compared to high-pass noise masking.

This decreased audibility results in decreased ERP amplitudes and increased ERP latencies, along with lower behavioral d' values and increased RTs. For the stimuli used in this study (/ba/, /da/), the effects of the low-pass noise are greatest beginning when the 1000 - 2000 Hz spectral region is masked. This is the frequency region containing the primary acoustic cues differentiating /ba/ from /da/ (i.e., second formant transition frequency).

Behavioral Measures

The mild/moderate threshold elevations produced by low-pass noise masking result in decreased d' scores. Changes in d' first begin with the 1000-Hz low-pass noise condition for 65-dB speech sounds, and with the 2000-Hz low-pass noise condition for 80-dB speech sounds. The d' scores were significantly smaller for responses to /ba/ than for /da/ at 65 dB, though not at 80 dB.

The moderate threshold elevations produced by the low-pass noise masking also result in increased RTs. As with d' , changes in RT first begin with the 1000-Hz low-pass noise condition at 65 dB, and with the 2000-Hz condition at 80 dB. Additionally, RTs to /ba/ are longer than those to /da/, even in the QUIET condition, though this effect increases as the low-pass noise cutoff is raised.

Behavioral results with low-pass noise masking differ from our previous high-pass noise studies (Chapters 3 and 4), in that, in the present study, changes in behavioral measures begin as the masker cutoff is raised, whereas changes in the previous studies begin as the masker cutoff is lowered. The similarity between the studies is that when spectral energy in frequency regions important for the discrimination of /ba/ and /da/ are masked, behavioral measures are affected. The present study indicates differences in behavioral responses to the two stimulus intensities. For 80-dB stimuli in the 1000-Hz low-pass condition, most or all of the spectral cues for /ba/ were masked, while some of the spectral cues for discrimination of /da/ (some of the second formant transition, and perhaps some burst frequency information) were still available. Therefore, subjects could differentiate the stimuli. When the low-pass noise cutoff was raised to 2000 Hz, the second and third formant transitions for /da/ were also masked, and subjects could not differentiate the stimuli. For 65-dB stimuli, less masking was required to mask spectral energy in the region of the second formant transition. The low-pass noise had a greater effect on RT for /ba/ than for /da/. The second formant transition for /ba/ is about 1100 Hz, whereas for /da/ the F2 transition is higher, at about 1800 Hz. Therefore, the second formant transition for /da/ remained audible for more low-pass noise conditions than did the second formant transition for /ba/.

Dubno and Ahlstrom have also found that speech recognition improved with increased speech intensity for normal subjects listening to low-pass masked speech stimuli. Further, as the low-pass masker cutoff frequency was raised, consonant recognition decreased, particularly when the filter slope of the masker was steep (Dubno and Ahlstrom, 1995). Dubno, Dirks and Ellison found that high-pass filtering of speech presented to normal listeners (similar to low-pass masking) results in decreased consonant recognition. Recognition scores for /b/ showed systematic decreases as the

filter cutoff was raised in octave-steps, especially when it was raised to 1400 Hz and above. Scores for /da/ showed large changes when the filter was raised to 2800 Hz and above (Dubno, Dirks and Ellison, 1989). Given the different task and type of stimuli used, their results are consistent with those of the present study where changes in recognition are seen when the low-pass noise masker is raised to 1000 Hz and above, and also when stimulus intensity is raised.

ERP Measures-Active Conditions

Decreased audibility of the speech sounds produced by low-pass noise masking results in increased latencies and decreased amplitudes of the ERP peaks. No studies examining the effects of low-pass noise masking on ERPs have previously been published. N1 amplitudes dropped off rapidly when the low-pass noise cutoff was raised to 2000 Hz and above for 65-dB speech sounds and to 4000 Hz and above for 80-dB speech sounds. Changes in N1 latency began with the 1000-Hz noise for both 65- and 80-dB speech sounds. As would be expected, latencies were longer for 65-dB speech sounds than for 80-dB speech sounds. Latencies for N1 were longer for /ba/ than for /da/, perhaps due to the lower frequency content of /ba/ relative to /da/. This finding is consistent with results of the previous high-pass noise studies (Chapters 3 and 4) and broadband noise studies (Whiting *et al.*, submitted). The lower frequency content of /ba/ relative to /da/ may be due to traveling wave delays at the cochlear level for /ba/ relative to /da/ which are manifested at the cortical level (Békésy, 1960; Hind, 1953). Additionally, different cortical representation of the two speech sounds, due, in part, to their differing frequency content is likely (e.g., Mendelson and Cynader, 1985; Phillips and Irvine, 1981; Ponton, Don, Waring, Eggermont and Masuda, 1993; Sams and Näätänen, 1991; Steinschneider, Arrezzo and Vaughan, 1990). Although N1 was present in all conditions where speech sounds were audible, the drop off in N1 amplitude as the low-pass masker was raised was sharper than seen with changes in the high-pass noise maskers (Chapters 3 and 4), particularly in response to 65-dB speech sounds. This may be due upward spread of masking, or to the larger contribution of low-frequency spectral regions on N1 amplitude (Chapter 4; Stapells and Martin, 1993). N1 amplitude is smaller in response to high-frequency tones than to low-frequency tones (e.g., Picton, Woods and Proulx, 1978) which may carry over into

smaller N1 amplitudes for speech sounds with higher frequency formant transitions (/da/) compared to speech sounds with a lower frequency formant transitions (/ba/). When the low-frequency content of the speech sounds was masked by the noise, only a small N1 could be elicited where stimuli were audible because most of the energy contributing to N1 was masked. The pattern of results seen for N1 reflect its function as an obligatory potential. It reflects the presence of audible speech energy, being present when speech sounds were audible, whether or not they were discriminable.

Changes in N2 amplitude resulting from the low-pass noise masking begin with the 2000-Hz low-pass noise masking, and amplitudes in response to the 65-dB speech sounds were smaller than were those in response to the 80-dB speech sounds. Changes in N2 latency begin with the 1000- to 2000-Hz low-pass noise conditions. Latencies were longer for /ba/ than for /da/.

As with N2, changes in P3 amplitude begin with the 2000-Hz low-pass noise condition. Changes in P3 latency begin at 1000-Hz for responses to the 65-dB speech sounds, and 2000-Hz for responses to the 80-dB speech sounds.

These results are fairly similar to our previous studies (Chapters 3 and 4), where changes in N2 and P3 amplitudes and latencies began with 1000-Hz high-pass noise masking. However, these changes began when the noise masker cutoff was *lowered* with high-pass noise masking, as opposed to *raised* with low-pass noise masking. The similarity is that when the spectral region containing the information necessary for differentiation of /ba/ and /da/ is masked (i.e., second formant transition), changes in N2 and P3 occur.

The pattern of results seen for N2 and P3 reflect their function as discriminative potentials. The masking first affected the spectral region containing the second formant transitions for the stimuli when the low-pass cutoff was raised to 1000 Hz for the 65 dB speech sounds. The transitions were not completely masked, however, and subjects were able to differentiate between the stimuli, though not with the accuracy (d' , amplitude) or speed (RT, latency) seen for lower low-pass noise cutoffs. Most subjects reported perceiving the sounds as /ba/ and /da/, or /a/ and /da/ in this condition, though they reported that distinguishing the sounds was difficult. For the 80-dB speech

sounds, subjects reported that distinguishing between /ba/ and /da/ was easy in the 1000-Hz low-pass noise condition, but reported difficulty distinguishing the speech sounds in the 2000-Hz low-pass noise condition. In this condition, most subjects reported that the speech sounds were /ba/ and /da/, or /a/ and /da/, but also mentioned that the sounds seemed quite distorted. When the low-pass noise masker cutoff was raised further, subjects that reported hearing the stimuli indicated they heard “/a/” and “/a/”, or reported that they heard something repetitive, but that the stimuli were no longer speech-like or distinguishable.

ERP Measures-Passive Conditions

A shorter ISI was used for the passive conditions in the present study compared to our previous study (Chapter 4). Due to increased efficiency of averaging in this study (a larger number of trials was presented in a given time period even with the decreased deviant probability compared with the previous study), the MMN obtained appeared larger and had clearer morphology than in our previous study (Chapter 4). The signal-to-noise ratios of the recordings were improved (i.e., quieter recordings and larger amplitude responses) because a larger number of deviant trials was collected within in a given time period, while MMN amplitude did not show a large decrease with the change in ISI. As with d' , and N2 and P3 amplitudes, significant changes in MMN amplitude begin with the 2000-Hz low-pass noise. Changes in MMN latency begin with 1000-Hz low-pass noise, and latencies in response to /ba/ are longer than MMN latencies in response to /da/. These results are consistent with our previous study (Chapter 4) where changes in MMN amplitude and latency with high-pass noise masking began with the 1000-Hz high-pass noise condition. In other words, when the spectral energy important for differentiating /ba/ and /da/ was masked, changes in MMN amplitude and latency are seen. The pattern of results for the MMN, like N2 and P3, reflect its discriminative function. MMN changes occurred even though subjects were not paying attention to the stimuli, indicating much of the change seen with noise masking is pre-attentive.

Relationship Between Behavioral and ERP Measures

As seen in Figure 15, the low-pass noise affected N1 differently than the other ERP or behavioral measures, particularly for responses to the 80-dB speech sounds. At 80 dB, the drop in response strength as the low-pass noise cutoff was raised was smaller for N1, and occurred at a different frequency compared to the other ERPs or behavioral d' . For both 65- and 80-dB speech sounds, steady increases in N1 latency occurred as the low-pass noise cutoff was raised. In contrast, changes in RT, MMN, N2 and P3 latencies were zero or gradual until the low-pass noise was raised to 1000 Hz for the 65-dB speech sounds, and to 2000 Hz for the 80-dB speech sounds. At these cutoffs, latencies increased sharply for all of these measures, though there were some differences in the amount of change that occurred at these points between the measures. For low-pass noise, ERP latencies were more sensitive to increased discrimination/task difficulty caused by the masking than were amplitudes. For responses to 65-dB speech sounds, most subjects reported that the discrimination task was difficult for the 1000 Hz low-pass noise condition. Significant changes in the latencies of these ERPs, as well as in behavioral reaction time, occurred with the 1000-Hz low-pass noise condition. In contrast, significant changes in behavioral d' , MMN, N2 and P3 amplitude did not change until the 2000-Hz low-pass noise condition. This pattern of results is similar to changes seen with broadband noise masking (Whiting *et al.*, submitted), where latency changes were more sensitive to noise masking than were amplitude changes. This finding is different, however, from those seen in the previous high-pass noise masking studies (Chapters 3 and 4), where significant changes in amplitude and latency both occurred when the high-pass noise cutoff was lowered to 1000 Hz. It appears that there are some instances when decreased audibility will affect both amplitudes and latencies, and some instances where latency is a more sensitive measure. It is therefore important to examine *both* response strength (i.e., amplitude) and timing (i.e., latency) measures.

Strong correlations were seen between behavioral d' scores and all ERP amplitude measures. The only strong correlations between behavioral d' scores and ERP latencies, however, were with N1 latency. This is perhaps because N1 indexed the presence of audible speech energy.

Although d' is a measure of the discriminability of the speech sounds, discriminability is also related to audibility. Sounds that are not audible cannot be discriminated. As would be expected, the d' measures also showed a strong relationship to response amplitude for the discriminative ERPs. The relationship of d' to the latency of these discriminative ERPs, however, was not strong. Correlations between RT and ERP latency were strong except for the correlation with MMN latency, which did not reach statistical significance. This is likely due to the large variability of the MMN and difficulty in determining MMN latency (e.g., Chapter 4; Kurtzberg, Vaughan, Kreuzer and Fliegler, 1995). In the previous study (Chapter 4), RT and MMN latency were significantly correlated. Finally, the correlations between RT and ERP amplitude show a progressive relationship, where earlier peaks (N1, MMN) showed small, nonsignificant correlations, and later peaks (N2, P3) showed moderate correlations. It makes sense that correlations between behavioral discrimination are greatest with ERP measures reflecting conscious discrimination and are not as strong for a pre-attentive, preconscious measure such as MMN. Furthermore, these behavioral and N2/P3 ERP measures were obtained simultaneously.

Implications

Cortical ERP and behavioral measures provide a window into the brain processing underlying speech perception. N1 indexes speech sound audibility, being present when speech sounds are audible, whether or not they are discriminable. The MMN indexes preconscious speech sound discrimination, being present when audible speech sounds are discriminable, whether or not the subject is paying attention. At least in the present paradigm, N2, P3 and behavioral measures index conscious speech sound discrimination, being present when audible speech sounds are discriminable, but only when the subject is paying attention.

These results have a number of implications for the study of patient populations. A high percent correct or d' score does not guarantee that the timing of brain processes is unchanged. As shown by this study, and by a previous study (Whiting *et al.*, submitted), noise maskers resulted in slowing of brain processes associated with the discrimination of the stimuli. In some cases, this slowing occurred before changes in d' scores (or percent correct).

ERP measures should be considered for those patients who cannot or will not provide accurate behavioral measures of speech audibility and discriminability (e.g., infants, difficult-to-test populations). N1 may be used to index speech sound audibility. The strong correlations between behavioral performance and discriminative ERPs (MMN, N2, P3) suggest that these discriminative ERPs may be used to index speech sound discrimination. If a MMN, N2, or P3 is elicited, then evidence is available that a patient's brain was able to differentiate, at a cortical level, between two speech sounds. There are, however, some limitations to these measures. First, N2 and P3 require the subject to pay attention to the sounds and to count or press a button to the deviant sounds. This is not possible for all subject populations, particularly those that we are more likely to assess using these potentials. Further, infants do not show "P3", although they do show P3-like cortical discriminative responses (Kurtzberg, 1989), appearing as a negative wave peaking between 700 - 800 ms after stimulus onset. The cortical discriminative response is present in young infants, but is less prominent with older infants. Additionally, these responses are sensitive to subject state and perhaps attention, which limit its use for clinical populations (Kurtzberg, Vaughan, Kreuzer and Fliegler, 1995). The MMN may provide an alternative index that, at a cortical level, the brain has differentiated between two speech sounds. Recordings of the MMN do not require subjects to pay attention, and the MMN can be elicited in infants and young children (e.g., Alho, Sainio, Sajaniemi, Reinikainen and Näätänen, 1990; Cheour-Luhtanen, Alho, Kujala, Sainio, Reinikainen, Renlund, Aaltonen, Eerola and Näätänen, 1995; Kraus, McGee, Micco, Sharma, Carrell and Nicol, 1993). There remain problems, however, with response presence and variability in infants and young children (Kurtzberg, Vaughan, Kreuzer and Fliegler, 1995). Further research is needed in order to determine the most efficient ERP measures of speech sound discrimination in difficult-to-test populations.

These waves may prove to be particularly useful for difficult-to-test populations with hearing loss. Electrophysiologic measures may be the only information available on an infant's hearing. Hearing aid fittings on these infants, therefore, are sometimes based on limited information. ERPs

may provide us with more information on the effectiveness of the amplification, and provide ways to monitor changes with amplification and aural (re)habilitation.

The acoustic cues differentiating certain speech sounds are not always available to hearing-impaired listeners. The cues may be completely inaudible, degraded, or distorted. The present study provides more information on changes in neural processing that occur when acoustic cues are clearly audible (e.g., QUIET condition), degraded (e.g., 1000 - 2000 Hz low-pass noise conditions), or inaudible (e.g., BBN condition). When the acoustic cues differentiating /ba/ from /da/ were degraded using low-pass noise masking, subjects required more time to process the speech sounds, and the strength of this processing (as reflected by ERP amplitudes) was reduced. This suggests that persons with hearing loss may show similar changes in neural processing. If this is true, ERPs may be used to examine these changes, as well as to examine the extent to which amplification remediates these changes. In this study, for example, increases in discriminative ERP latencies occurred for 65-dB speech sounds when the low-pass noise masking was raised to 1000 Hz. When the speech sounds were amplified by 15 dB, to an 80-dB presentation level, the latency increases did not occur until the noise masking cutoff was raised to 2000 Hz. Further research examining changes in neural processing with hearing loss and with amplification are clearly needed. Additionally, ERPs have been used to predict emerging language function (Kurtzberg, 1989; Kurtzberg, Stapells and Wallace, 1988). It would be useful to examine whether ERPs could be used, with or without amplification, to predict the acoustic cues that are available to a child with hearing loss, and perhaps to predict the language skills that a child with hearing loss will develop.

The results seen with decreased audibility due to low-pass noise masking may be applicable to patients with peripheral hearing loss. The masked audiograms produced by the noise masking are similar to those seen in patients with low- and mid- frequency sensorineural hearing loss, and similar in configuration, though not necessarily degree, to those seen with conductive loss such as otitis media. If this is true, even moderate low-frequency hearing loss produces slowing of brain processes and decreases in the strength of those processes involved in the evaluation of speech stimuli. This alteration in brain processing of the speech sounds conceivably could result in

difficulties with speech perception. Persons with low-frequency hearing loss not only have difficulty discriminating /ba/ and /da/, but may show difficulty with vowel perception, timing cues, prosody, etc. Further studies with subjects with hearing loss are needed to determine whether the amplitude and latency changes seen in this study are comparable to those seen with hearing loss, or whether hearing loss has further effects on neural processes.

5F. Acknowledgements

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Table 1. Average mean-MMN amplitudes across the subjects (n=10) are displayed for /ba/ and /da/ for all of the low-pass noise masking conditions, along with corresponding standard deviations.

		QUIET	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	BBN
65 dB	/ba/ <u>M</u>	-1.03	-0.93	-0.76	-0.27	-0.27	0.00	-0.08
	s.d.	0.92	1.29	0.81	1.05	0.86	0.68	1.19
	/da/ <u>M</u>	-0.75	-0.77	-1.22	-0.94	-0.36	-0.41	-0.27
	s.d.	1.33	0.91	1.74	1.19	0.73	1.09	0.67
80 dB	/ba/ <u>M</u>	-0.74	-0.65	-1.24	-0.57	-0.27	0.54	0.44
	s.d.	1.08	0.60	0.76	0.80	0.82	1.09	1.02
	/da/ <u>M</u>	-1.18	-1.07	-1.28	-0.44	0.16	0.33	-0.02
	s.d.	1.07	1.67	1.04	1.49	0.97	0.87	0.89

Table 2. Results of correlational analyses between behavioral [sensitivity (d') and reaction time (RT)] and ERP [N1, MMN, N2, P3] measures. Shown are Pearson product-moment correlation coefficients (r) and number of measures (N).

		AMPLITUDE				LATENCY			
		<u>N1</u>	<u>MMN</u>	<u>N2</u>	<u>P3</u>	<u>N1</u>	<u>MMN</u>	<u>N2</u>	<u>P3</u>
d'	r	.65*	.67*	.70*	.80*	-.66*	-.06	-.03	-.25*
	N	281	281	281	281	101	129	161	161
RT	r	-.18	-.06	-.25*	-.49*	.60*	.13	.56*	.65*
	N	159	159	161	161	81	129	161	161

* $p < .01$

Figure Captions

Figure 1. Mean (top) and standard deviation (bottom) behavioral pure-tone masked and nonmasked audiograms across the 10 subjects are displayed in dB SPL as a function of pure-tone frequency. Audiograms are shown for the QUIET (nonmasked) condition, 250 Hz through 4000 Hz low-pass noise masked conditions, and the broadband noise (BBN) condition.

Figure 2. The top graph displays d' measures of the discriminability of the stimuli as a function of noise masking condition, along with corresponding standard deviations. The lower graph displays reaction times as a function of noise masking condition, along with corresponding standard deviations. Circles indicate the data for /ba/ and triangles indicate the data for /da/. Responses to the 65 dB ppe SPL speech sounds are indicated by the closed symbols; responses to the 80 dB ppe SPL speech sounds are indicated by the open symbols.

Figure 3. The grand mean waveforms recorded in all of the noise conditions to the /ba/ and /da/ stimuli are displayed for the 65 dB ppe SPL active discrimination condition. Responses to stimuli presented as standards are displayed for Cz (thin line); responses to stimuli presented as deviants are displayed for Pz (thick line). N1, N2, and P3 are indicated.

Figure 4. The grand mean difference waveforms in all of the noise conditions to the /ba/ and /da/ stimuli are displayed for the 65 dB ppe SPL active discrimination condition. Responses are displayed for Cz. N2 is indicated.

Figure 5. The grand mean waveforms recorded in all of the noise conditions to the /ba/ and /da/ stimuli are displayed for the 80 dB ppe SPL active discrimination condition. Responses to stimuli presented as standards are displayed for Cz (thin line); responses to stimuli presented as deviants are displayed for Pz (thick line). N1, N2, and P3 are indicated.

Figure 6. The grand mean difference waveforms in all of the noise conditions to the /ba/ and /da/ stimuli are displayed for the 80 dB ppe SPL active discrimination condition. Responses are displayed for Cz. N2 is indicated.

Figure 7. The top graph displays the effects of the low-pass noise masking on mean N1 amplitudes. The lower graph displays the effects of the low-pass noise masking on mean N1 latencies. Circles indicate the data for /ba/; triangles indicate the data for /da/. Responses to the 65-dB speech sounds are indicated by the closed symbols; responses to the 80-dB speech sounds are indicated by the open symbols.

Figure 8. The top graph displays the effects of the low-pass noise masking on mean N2 amplitudes. The lower graph displays the effects of the low-pass noise masking on mean N2 latencies. Circles indicated the data for /ba/; triangles indicate the data for /da/. Responses to the 65-dB speech sounds are indicated by the closed symbols; responses to the 80-dB speech sounds are indicated by the open symbols.

Figure 9. The top graph displays the effects of the low-pass noise masking on mean P3 amplitudes. The lower graph displays the effects of the low-pass noise masking on mean P3 latencies. Circles indicate the data for /ba/; triangles indicate the data for /da/. Responses to the 65-dB speech sounds are indicated by closed symbols; responses to the 80-dB speech sounds are indicated by open symbols. P3 associated with "hit" button-press responses is indicated by dashed lines for 65-dB speech sounds and by solid lines for 80-dB speech sounds.

Figure 10. The grand mean waveforms recorded in all of the noise conditions to the /ba/ and /da/ stimuli are displayed for the 65 dB ppe SPL passive condition. Responses to stimuli presented as standards (thin line) and deviants (thick line) are displayed for Cz. N1 and MMN are indicated.

Figure 11. The grand mean difference waveforms in all of the noise conditions to the /ba/ and /da/ stimuli are displayed for the 65 dB ppe SPL passive condition. Responses are displayed for Cz. MMN is indicated.

Figure 12. The grand mean waveforms recorded in all of the noise conditions to the /ba/ and /da/ stimuli are displayed for the 80 dB ppe SPL passive condition. Responses to stimuli presented as standards (thin line) and deviants (thick line) are displayed for Cz. N1 and MMN are indicated.

Figure 13. The grand mean difference waveforms in all of the noise conditions to the /ba/ and /da/ stimuli are displayed for the 80 dB ppe SPL passive condition. Responses are displayed for Cz. MMN is indicated.

Figure 14. The top graph displays the effects of the low-pass noise masking on average peak-MMN amplitudes. The lower graph displays the effects of the low-pass noise masking on mean MMN latencies. Circles indicated the data for /ba/; triangles indicate the data for /da/. Responses to the 65-dB speech sounds are indicated by the closed symbols; responses to the 80-dB speech sounds are indicated by the open symbols.

Figure 15. Response strength (top) and latency change (bottom), normalized to the QUIET condition, are displayed as a function of low-pass noise masking condition for 65- and 80-dB ppe SPL speech sounds. N1 is indicated by squares, MMN is indicated by circles, P3 is indicated by diamonds, and behavioral results are indicated by the letter "B". Data are pooled across /ba/ and /da/. Results for N2 are not shown.

Figure 1

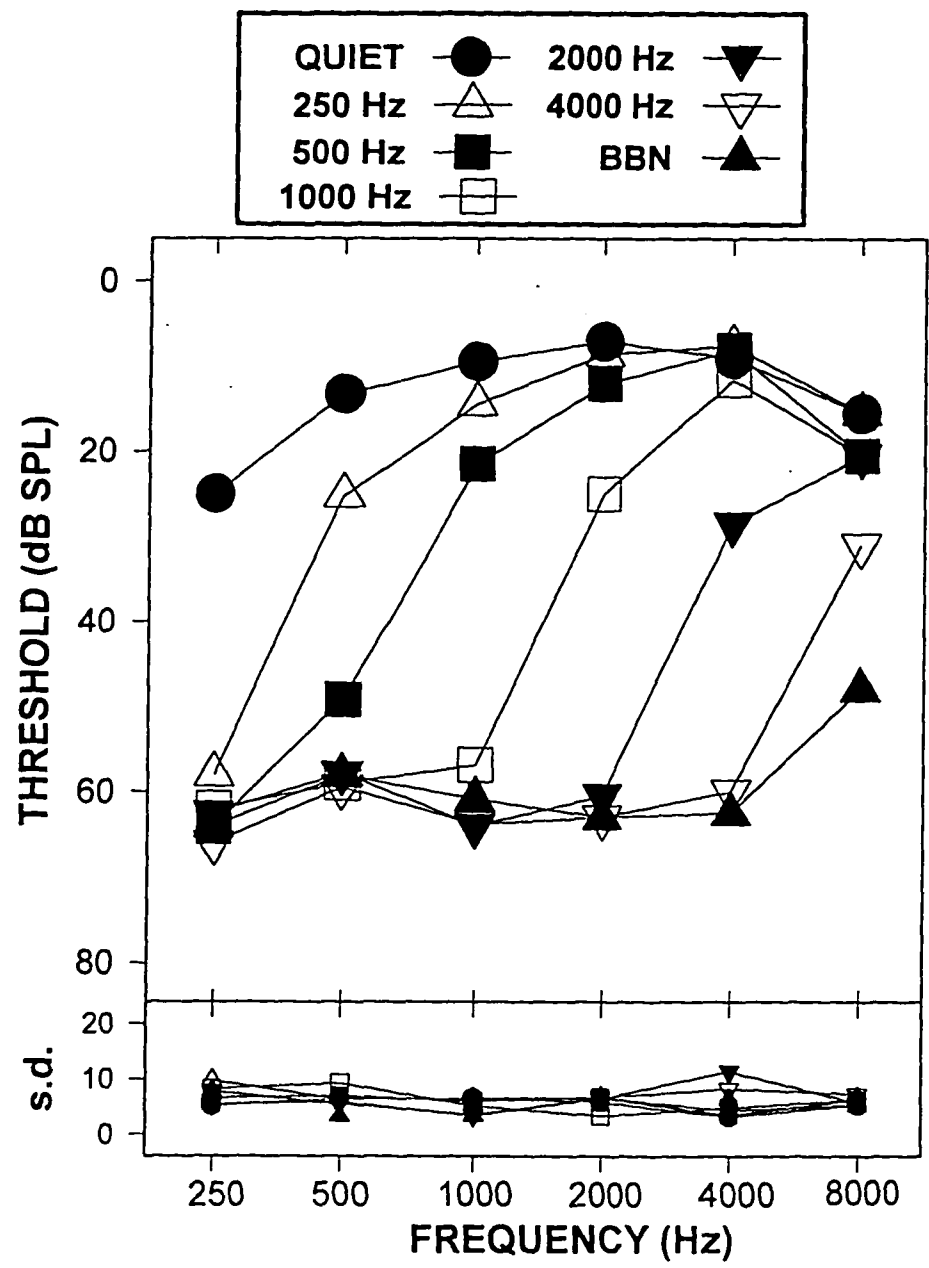


Figure 2

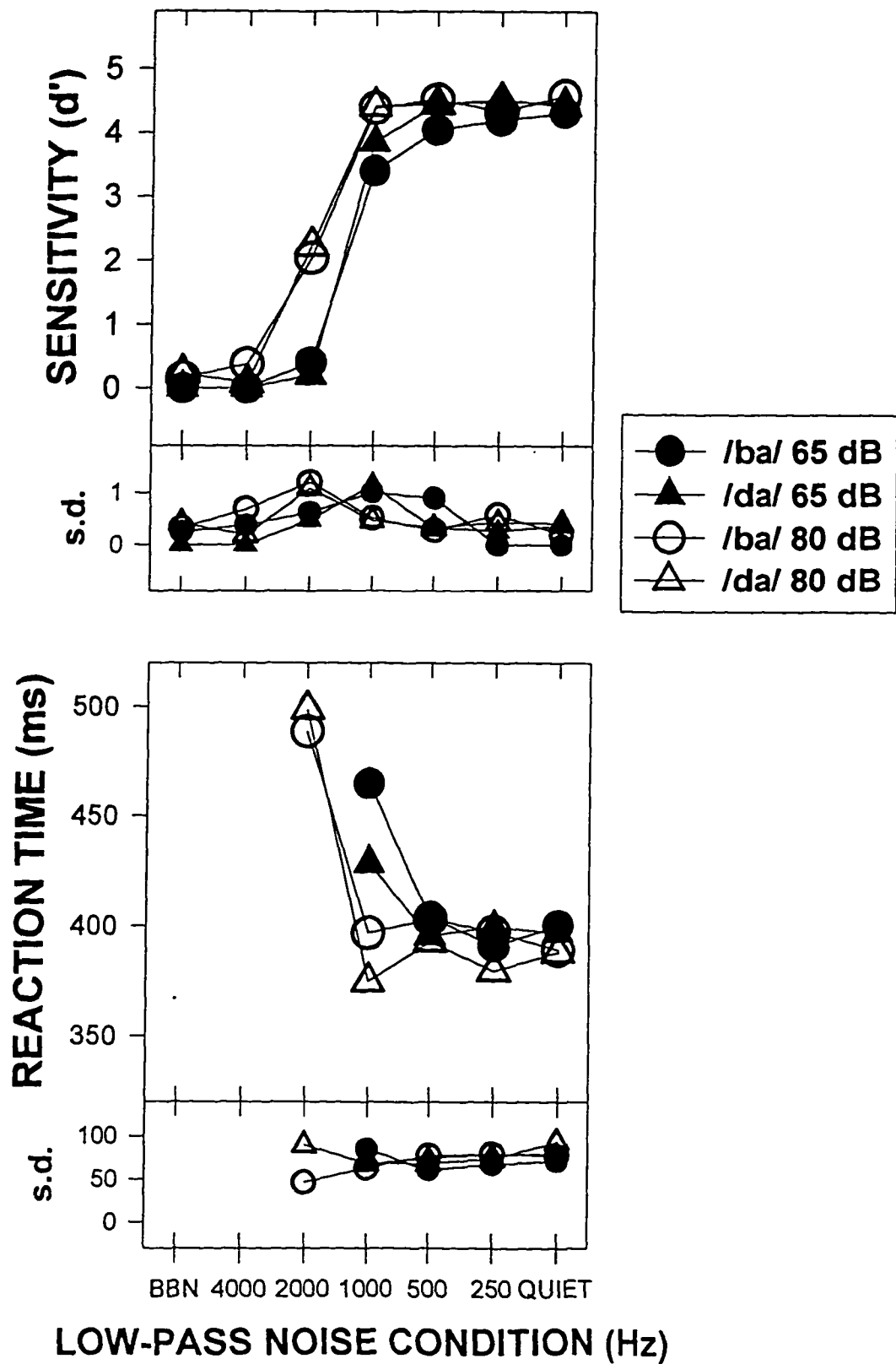


Figure 3

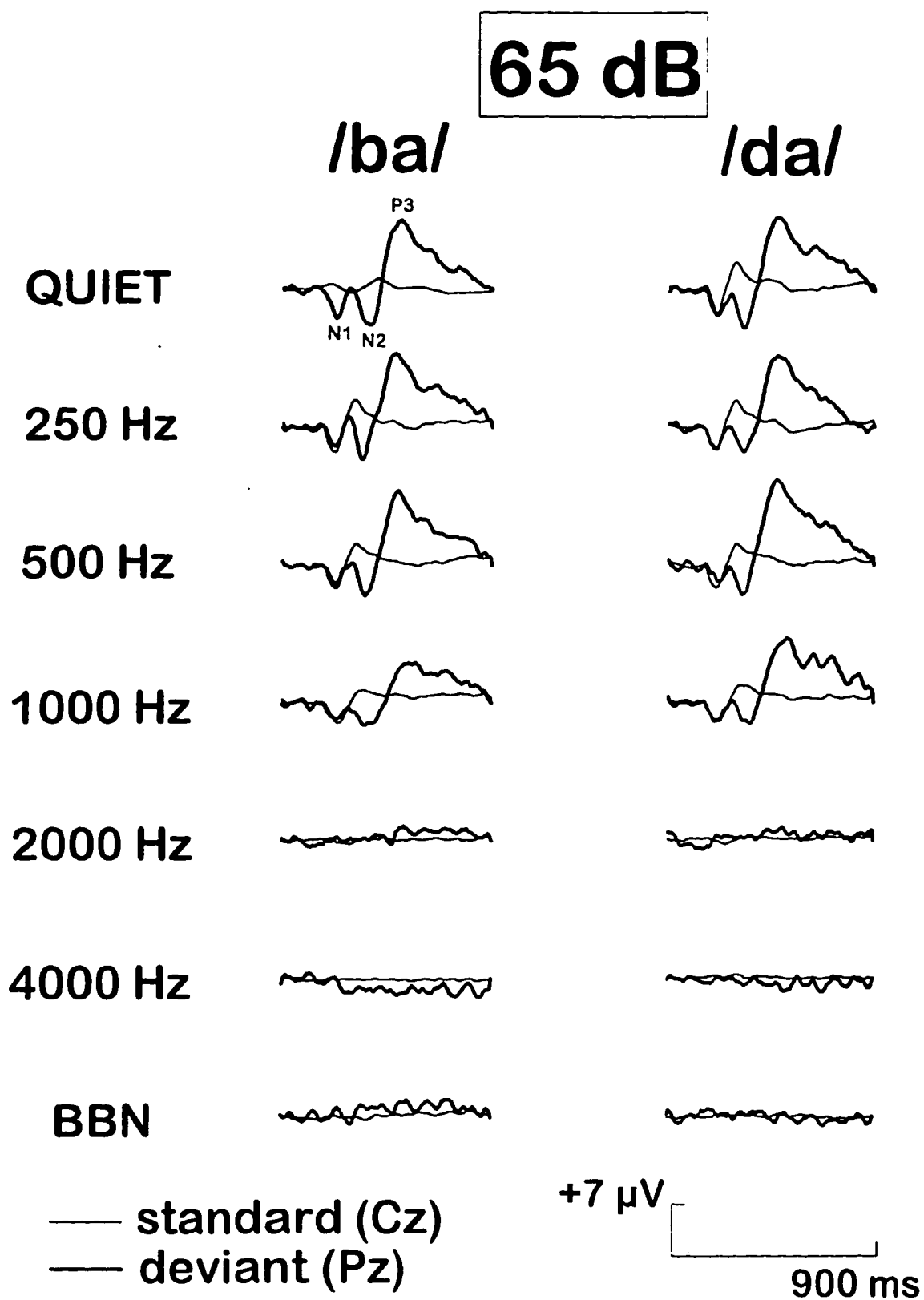


Figure 4

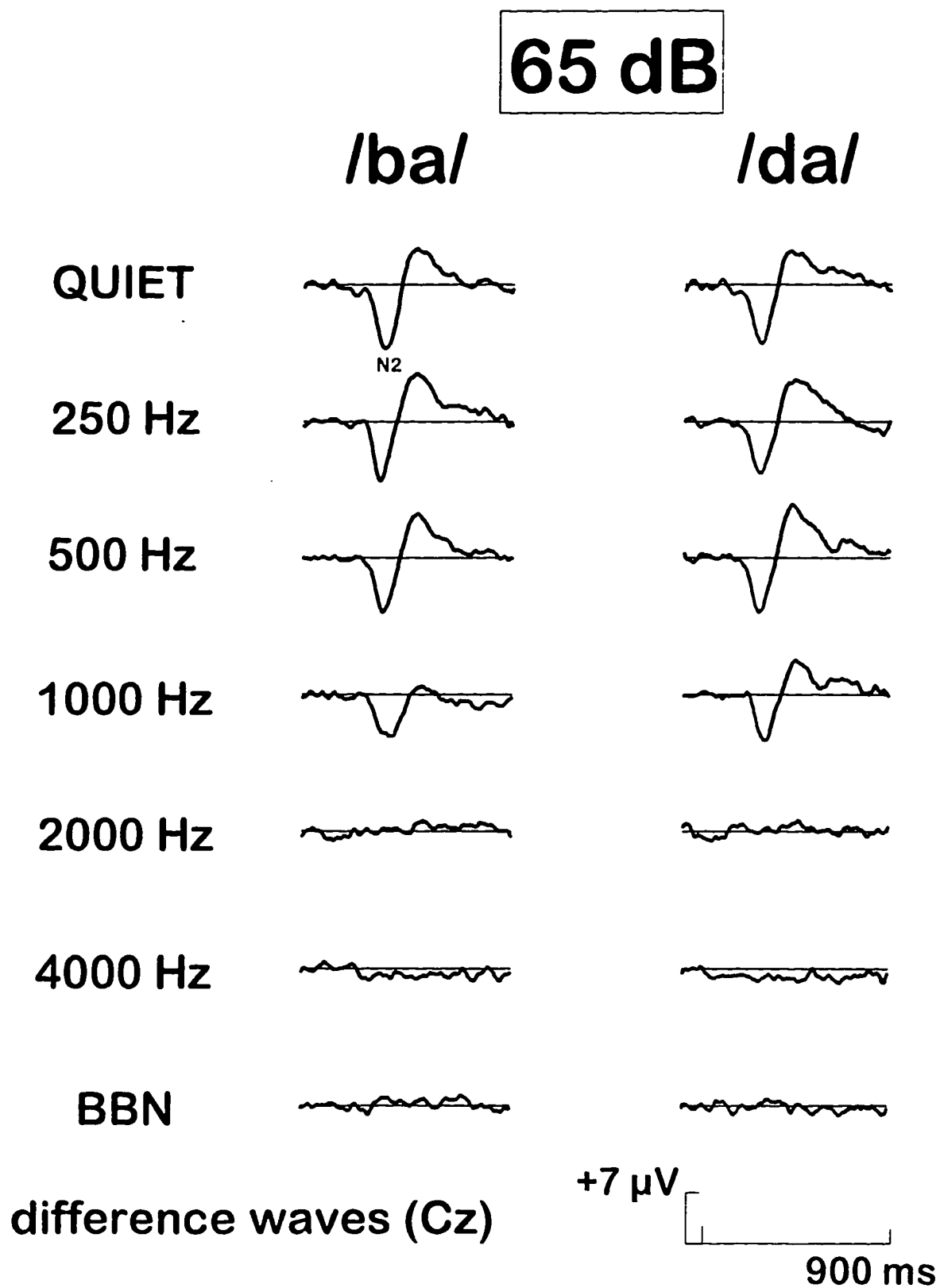


Figure 5

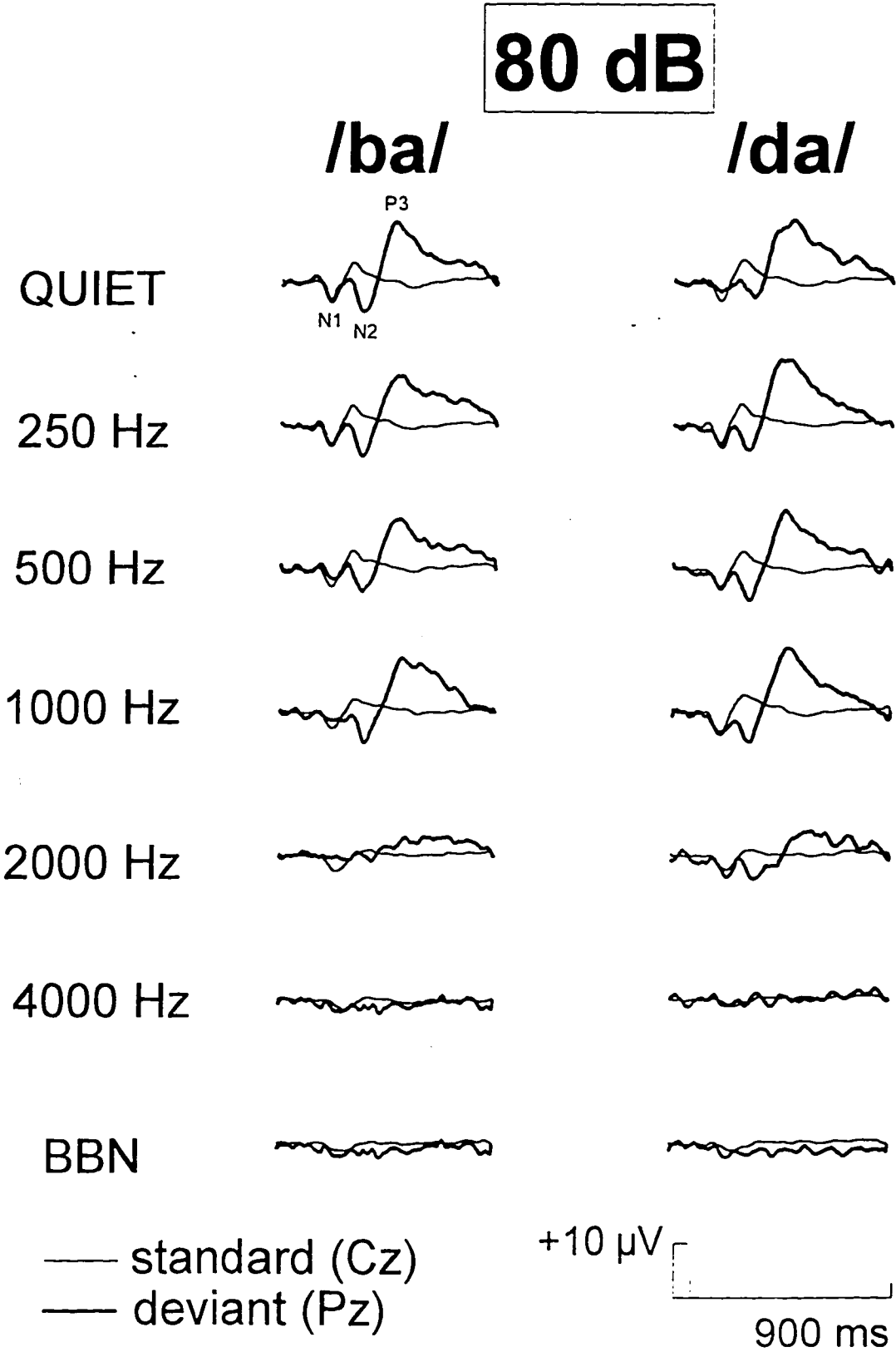


Figure 6

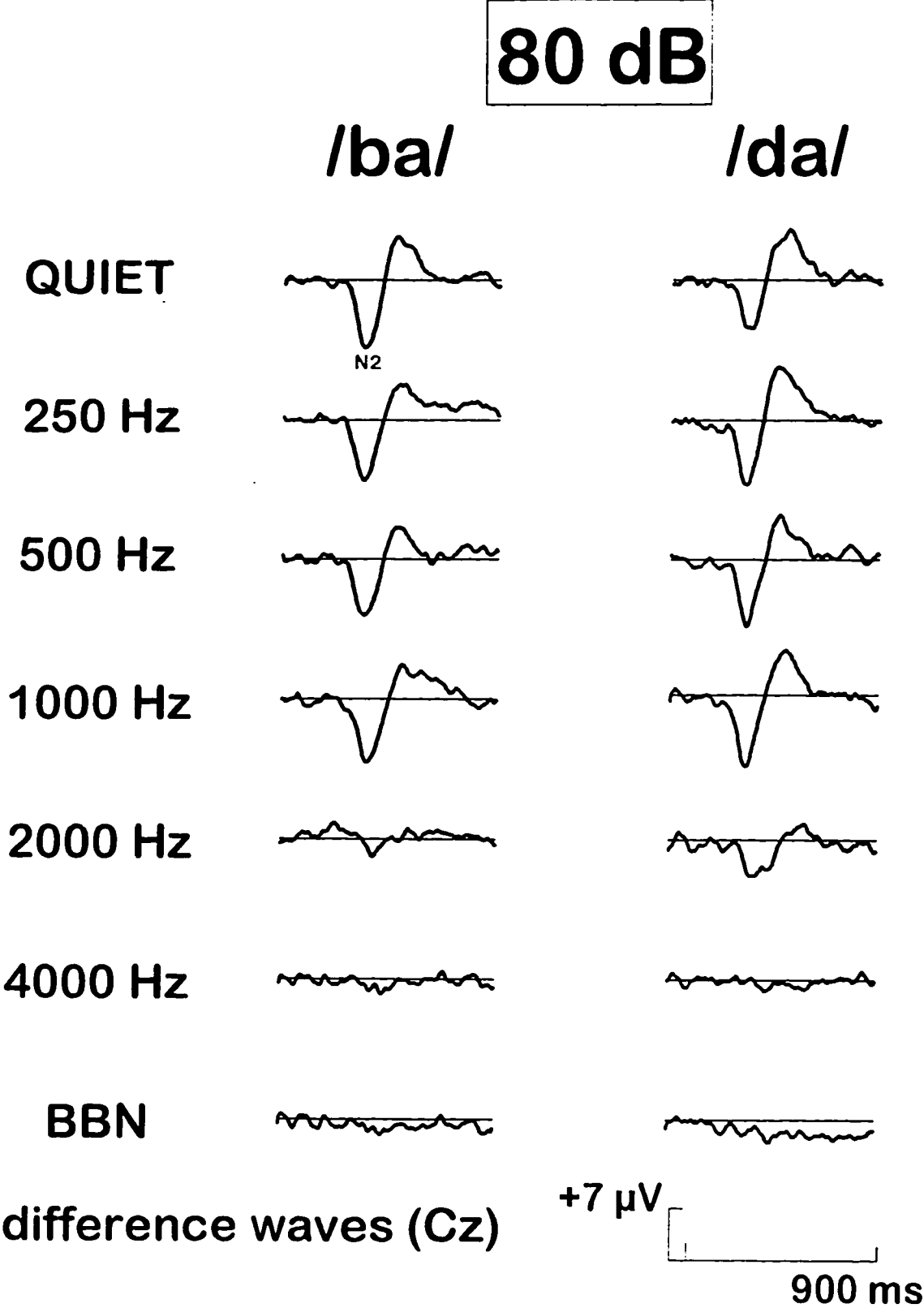


Figure 7

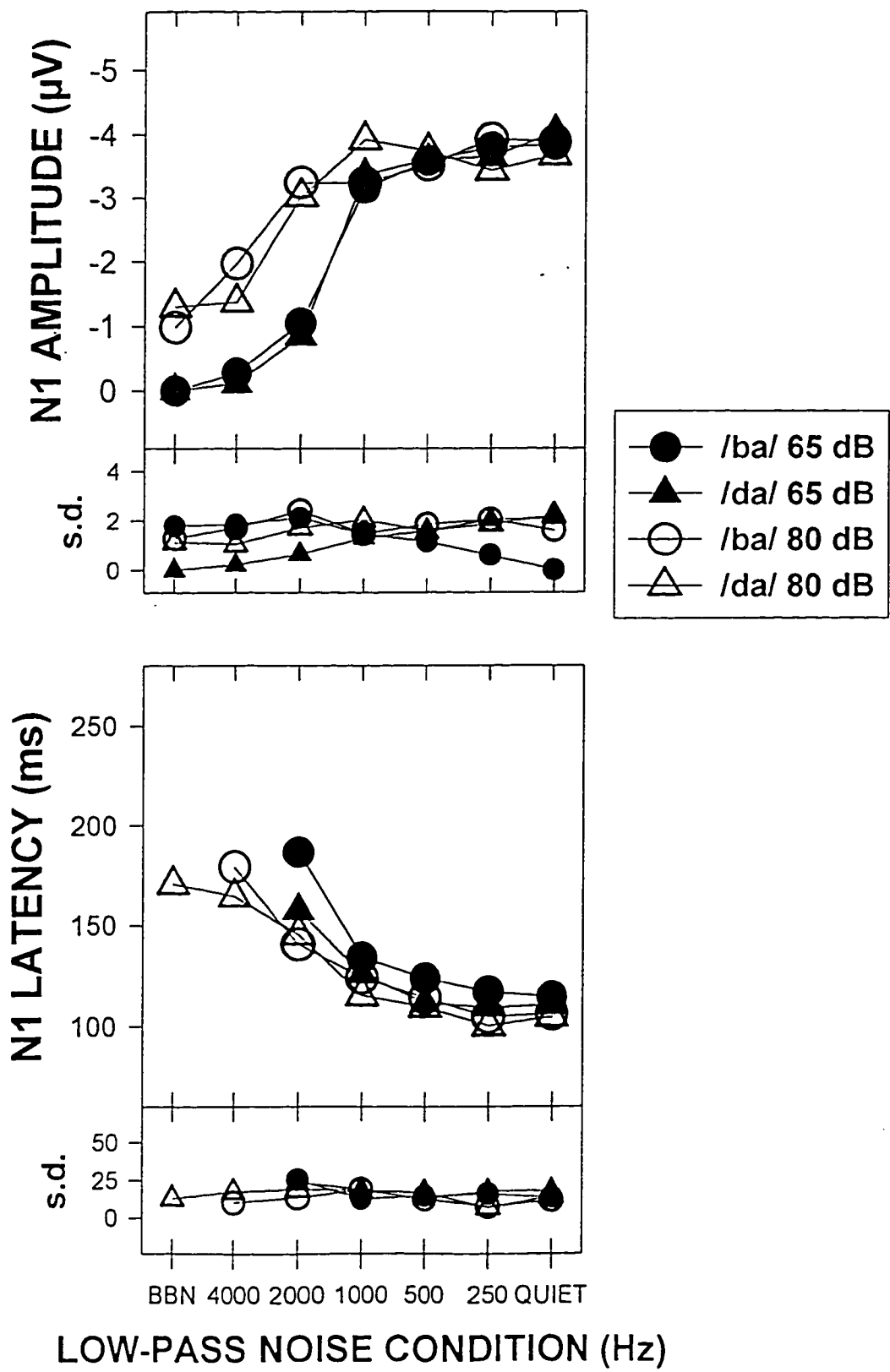


Figure 8

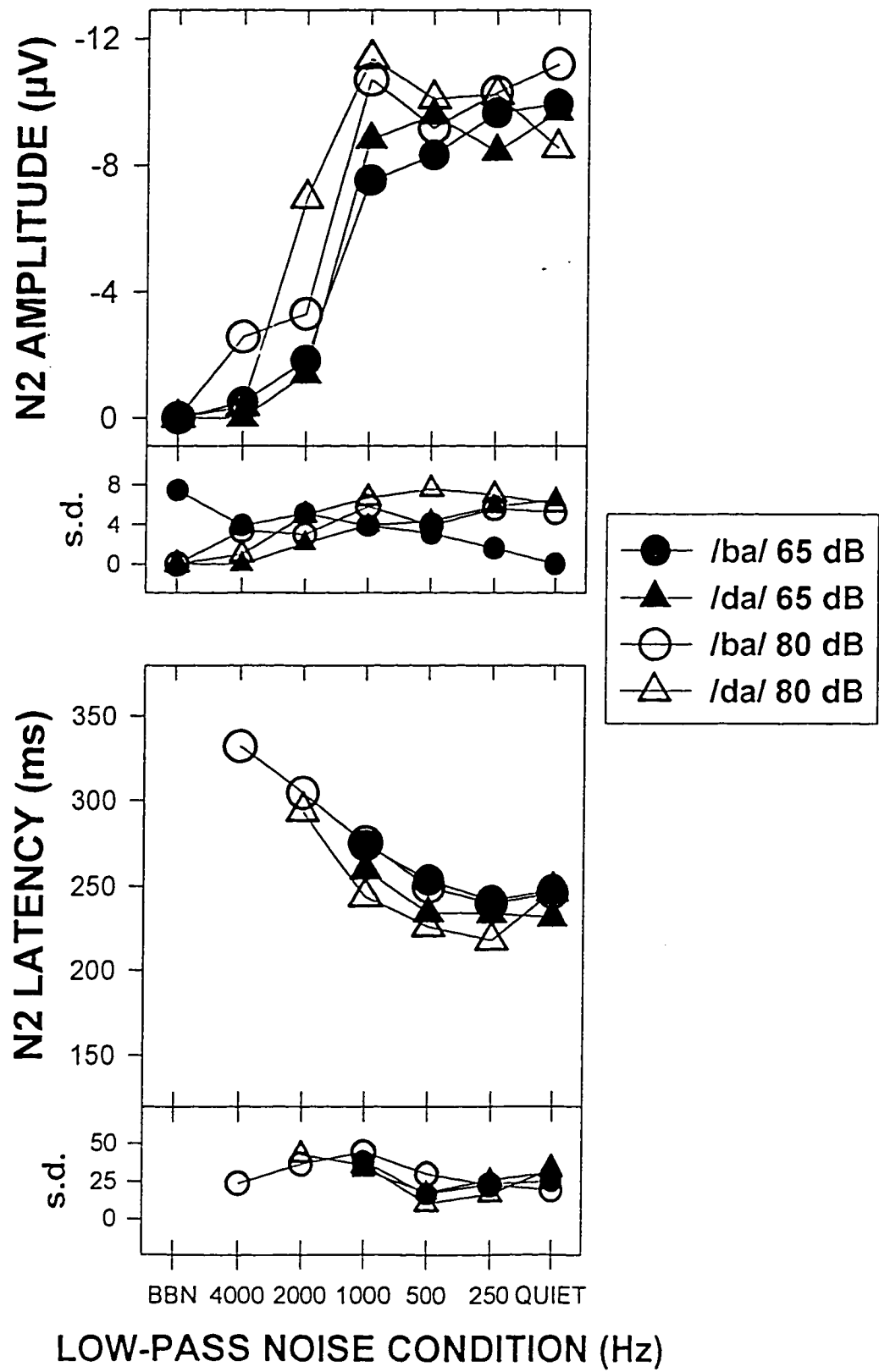


Figure 9

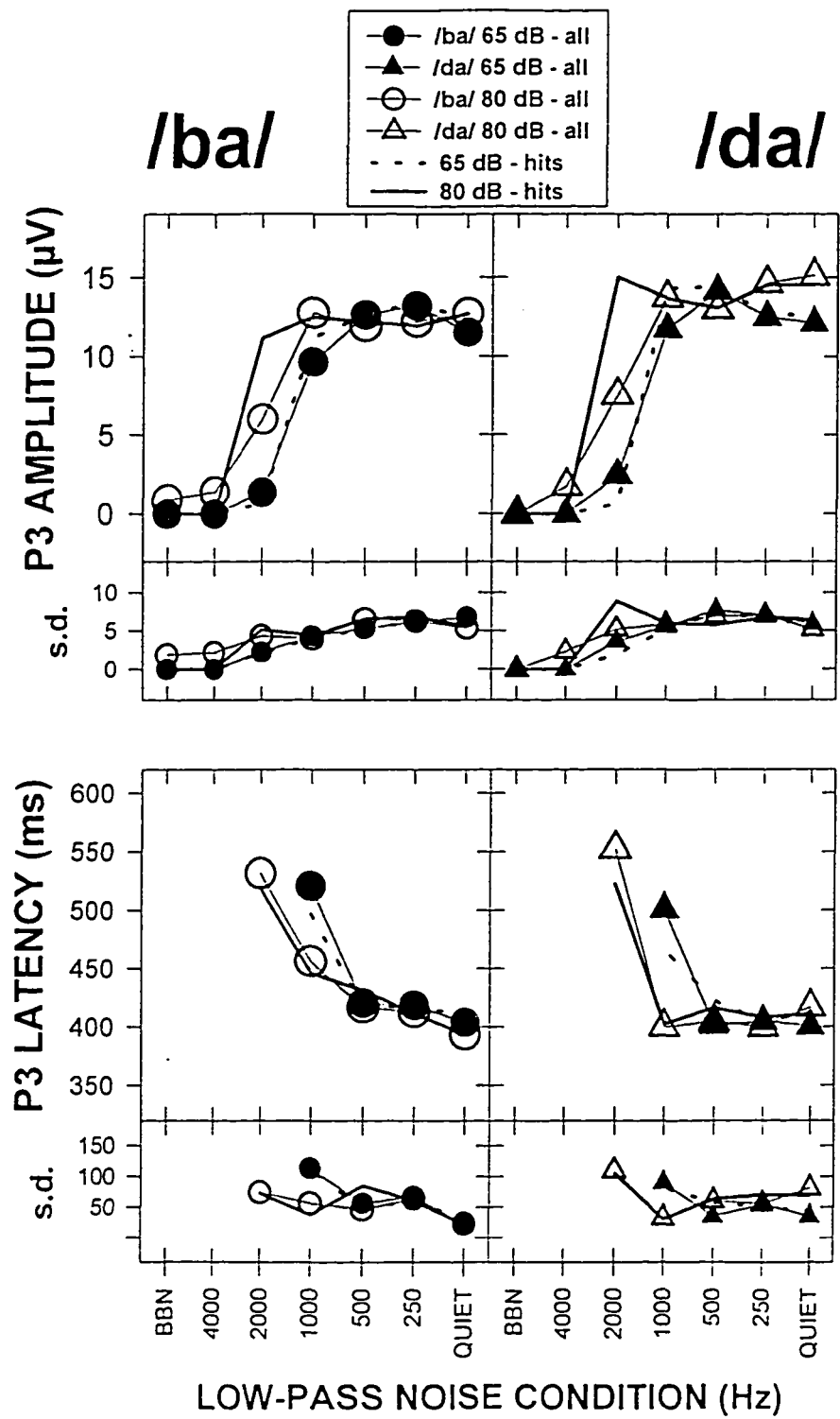


Figure 10

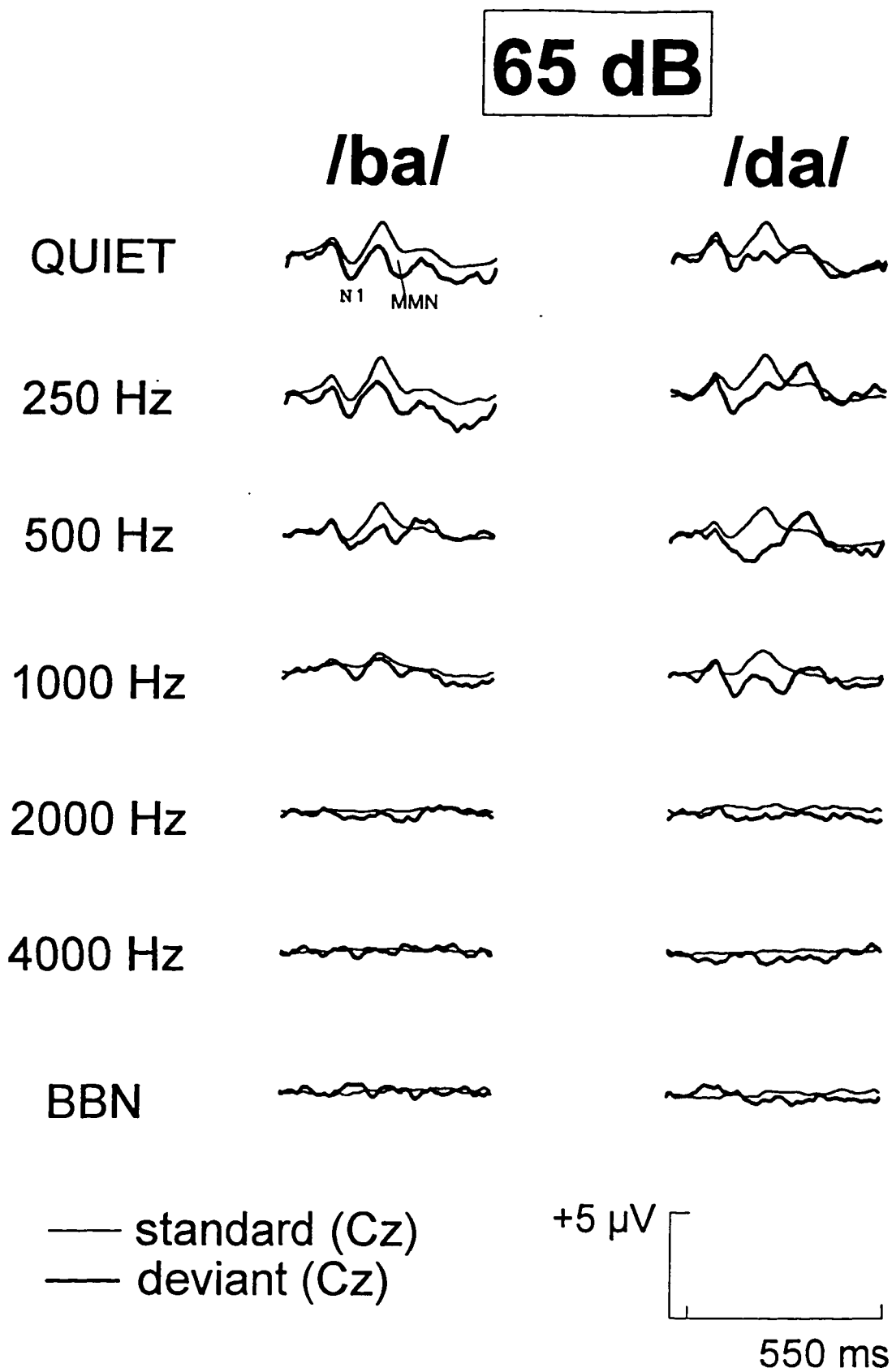


Figure 11

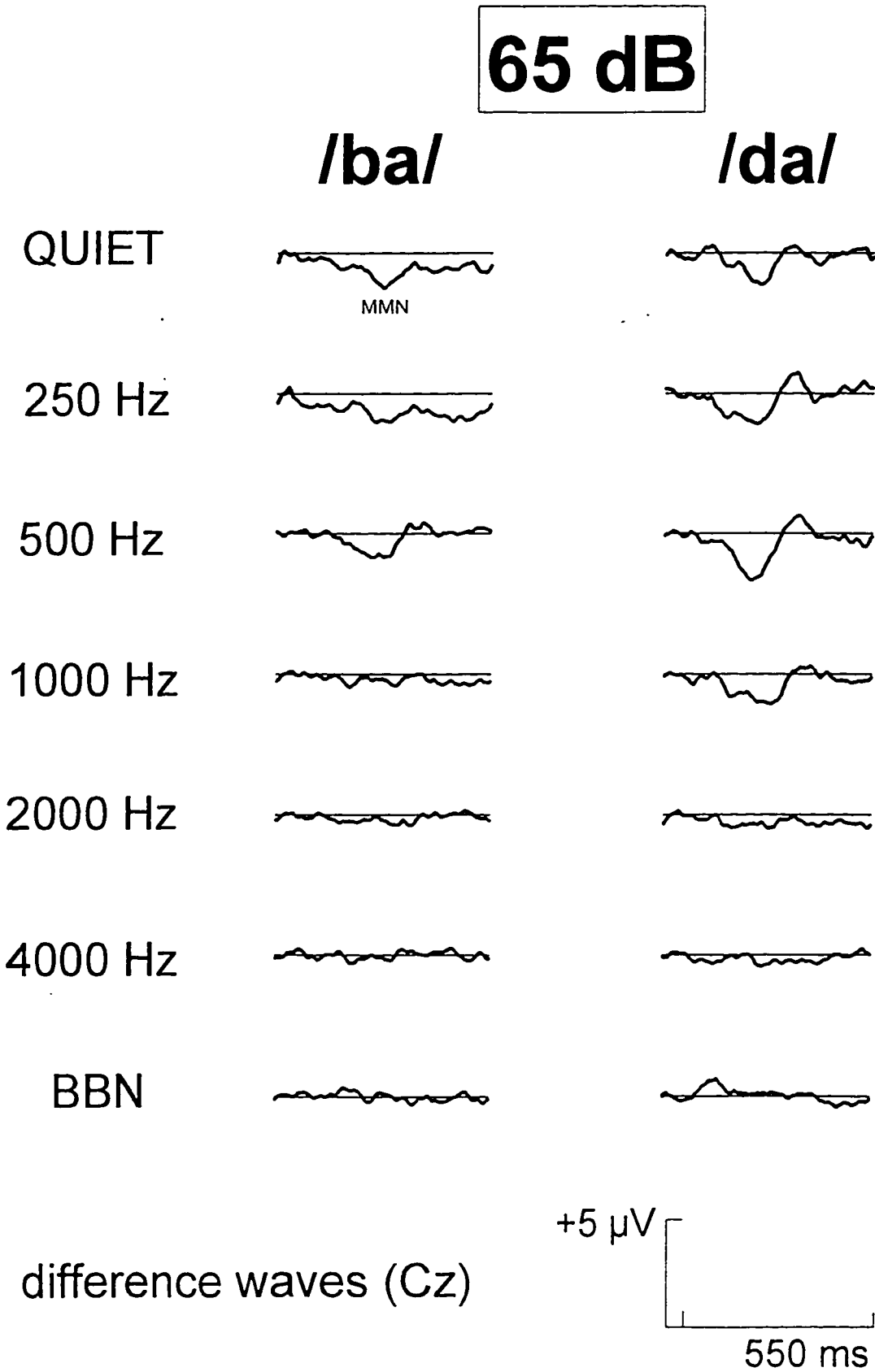


Figure 12

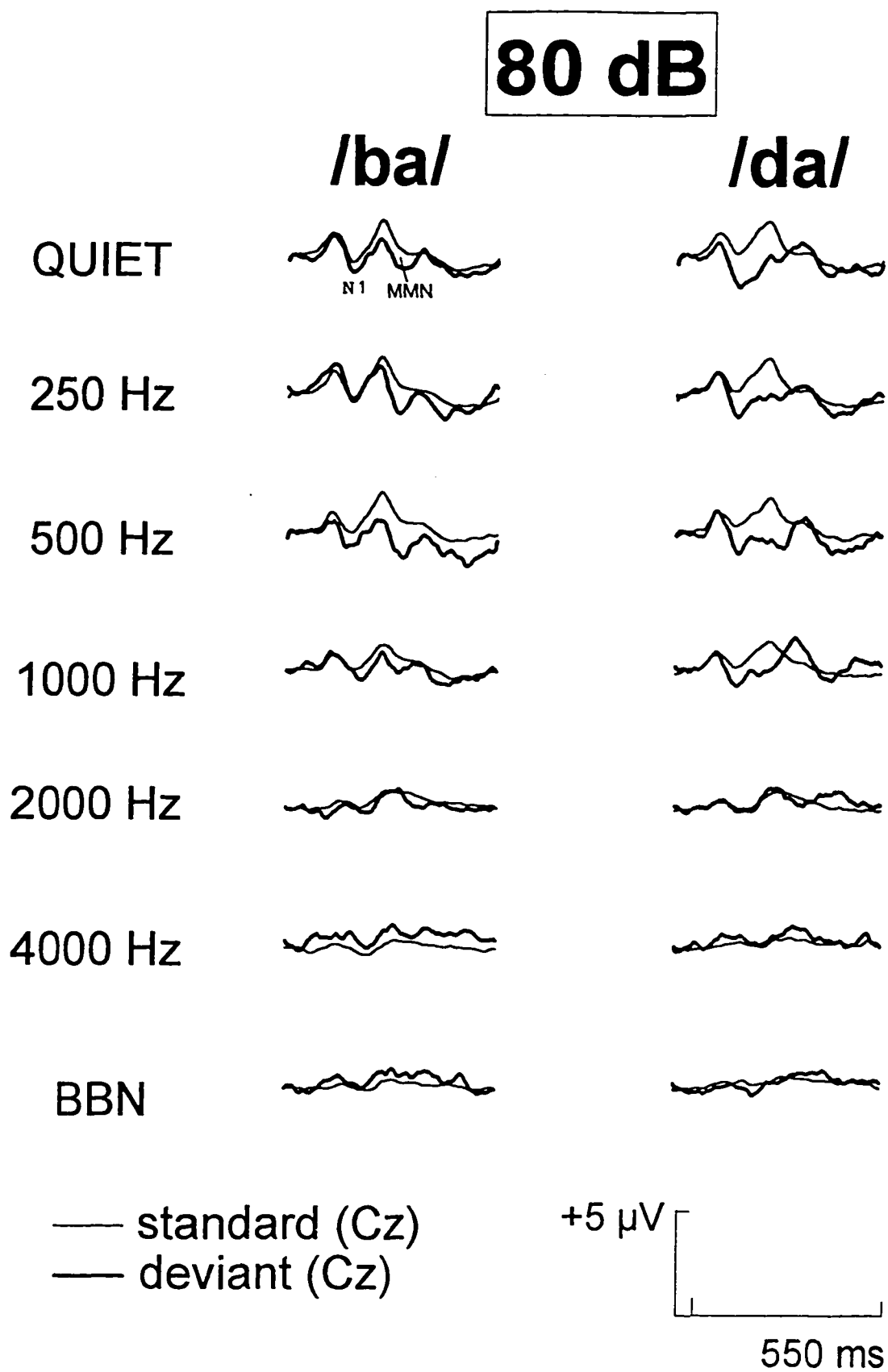


Figure 13

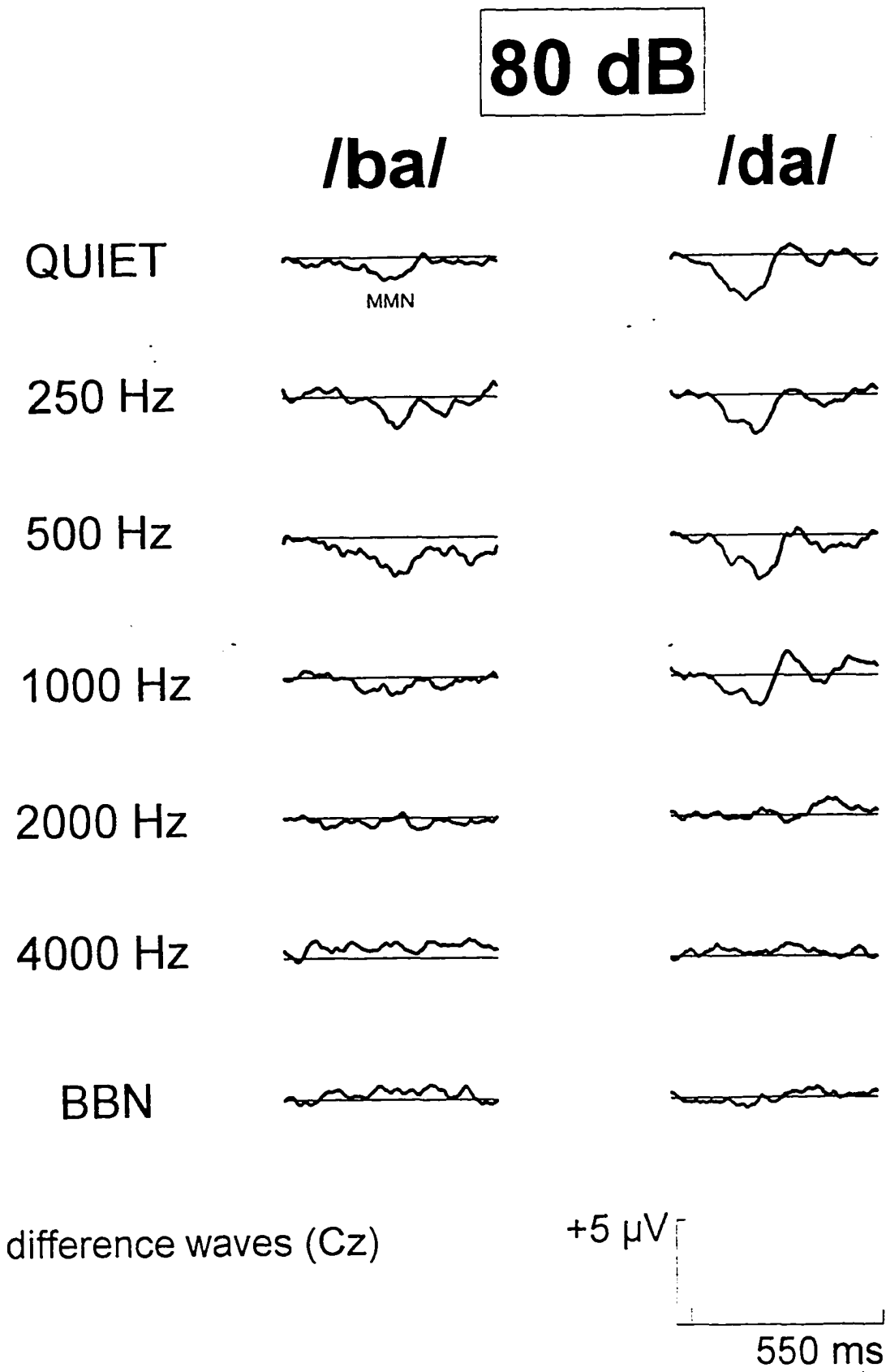


Figure 14

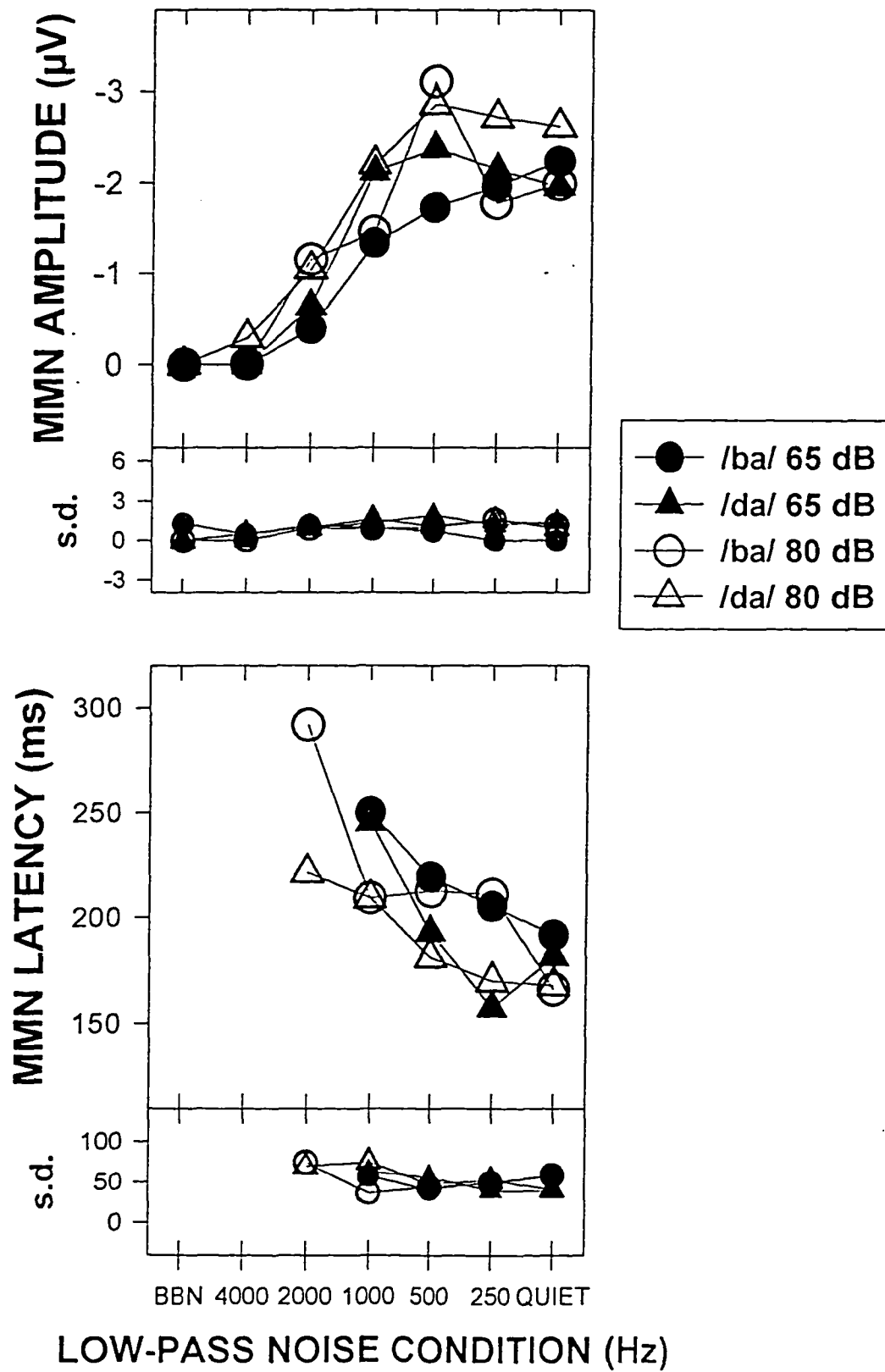
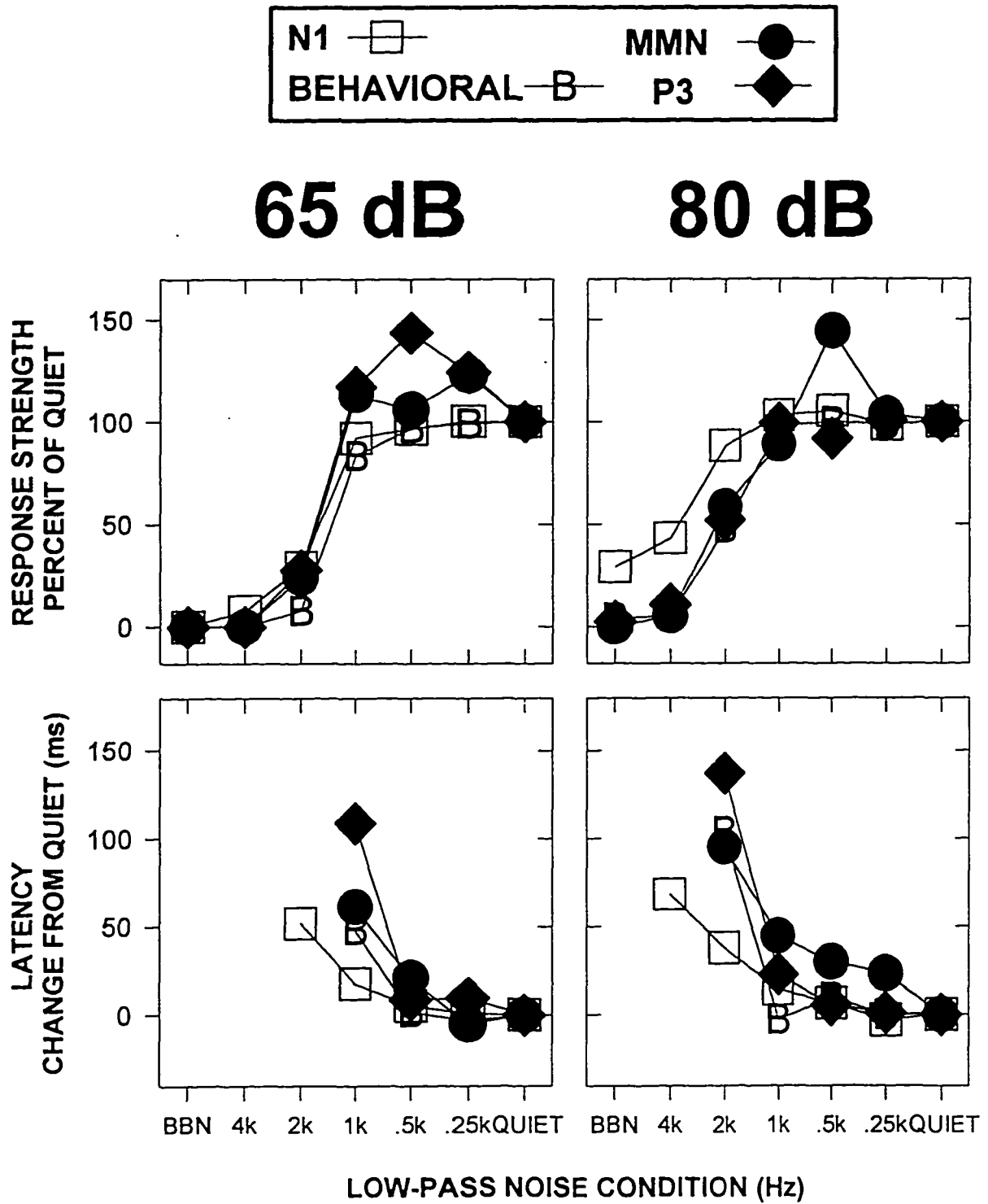


Figure 15



Chapter 6

**The contributions of selected frequency regions to behavioral
and electrophysiological responses to /ba/ and /da/.**

6A. Abstract

This paper examines the contributions of selected frequency regions to behavioral (d' , RT) and electrophysiological (N1, MMN, N2, P3) responses to speech sounds /ba/ and /da/. Data from the previous studies (Chapters 3, 4, and 5) were normalized (relative to responses in the QUIET condition) to allow comparison. ERP amplitudes and behavioral d' scores were expressed in terms of response strength (percent of amplitude in the QUIET condition). ERP latencies and behavioral reaction times were expressed in terms of latency change (ms change from the QUIET condition). After this normalization, results for high-pass and low-pass noise masking conditions were graphed for each ERP and behavioral measure. The “crossover frequency”—the frequency at which the high- and low-pass noise masking results intersect—was calculated. Results of the crossover frequency analyses indicated clear differences in the pattern of results for response strength and latency change between N1 and the other measures (behavioral, MMN, N2, P3). The crossover frequency for N1 was lower in frequency compared to the other measures (behavioral, MMN, N2, P3), with the exception of the crossover frequency for N1 response strength for 80-dB speech sounds, which occurred at higher frequencies compared to the other measures. In addition, the response strength at the crossover frequency was larger for N1 compared to the other measures. Latency change at the crossover frequency showed progression, with the smallest latency change occurring for N1, larger changes for MMN, N2 and RT, and largest changes occurring for P3. The crossover frequency tended to occur at higher frequencies for 80-dB speech sounds compared to 65-dB speech sounds. Additionally, the crossover frequency occurred at higher frequencies for responses to /da/ compared with responses to /ba/. The crossover frequency and the response strength at the crossover frequency for behavioral and ERP measures were similar, with the exception of N1. This study provides additional information on the effects of decreased audibility produced by spectrally shaped noise masking on behavioral and electrophysiological responses to speech sounds /ba/ and /da/. The results have implications for the functional significance of ERPs.

6B. Introduction

It is well known that the most important frequency region for consonant recognition is around 1500 to 2000 Hz (e.g., Boothroyd, 1978; Boothroyd, 1993; Fletcher, 1953; Hirsh, Reynolds and Joseph, 1954; Kryter, 1960; Miller and Nicely, 1955). This is the frequency region of the second formant. The second formant provides information about vowel place and consonant place of articulation (e.g., Boothroyd, 1993). Contributions to speech recognition from frequencies above and below this frequency range drop off to near-zero at 250 Hz and 7000 Hz. Approximately half of the information for in the acoustic spectrum for speech falls between 1000 and 3000 Hz, the region of the second formant (e.g., Boothroyd, 1993). More specifically, about half of the acoustic information important for the recognition of consonant place of articulation is in the spectral region of 880 - 2650 Hz (e.g., Boothroyd, 1993; Miller and Nicely, 1955).

Contributions of different spectral regions to speech recognition are typically examined by filtering out spectral regions and examining resultant speech recognition performance (e.g., Dubno and Ahlstrom, 1995; Dubno, Dirks and Ellison, 1989; Miller and Nicely, 1955). When this is done by systematic high-pass and low-pass filtering of the speech signal, it is common to graph the speech recognition score as a function of the filter cutoff. It is then possible to calculate the point where the high-pass and low-pass filtered speech recognition curves intersect (Miller and Nicely, 1955). This point of intersection is known as the "crossover frequency". Examination of the crossover frequency allows for an evaluation of the relative contributions of different parts of the frequency spectrum to speech recognition. Specifically, when high-pass and low-pass functions are plotted on the same graph, the frequency at which the two functions cross divides the frequency scale into two equivalent parts. The frequencies above the crossover frequency are equally important to speech recognition as the frequencies below the crossover frequency (Miller and Nicely, 1955). Thus, half of the information important for speech recognition is contained above this frequency and half below this frequency.

Several studies have examined the crossover frequency for various speech stimuli. French and Steinberg (1947) found that the crossover frequency as a function of filtering of speech was 1700-1900 Hz. Hirsh and colleagues obtained a similar value of 1700 Hz (Hirsh, Reynolds and Joseph, 1954). Miller and Nicely (1955) found that the crossover frequency was 1550 Hz for consonant recognition, and 1900 Hz for recognition of place of articulation. In otherwords, high-frequency information was more important for recognition of place of articulation than for overall consonant recognition. Boothroyd obtained a crossover frequency for consonant recognition of 1700 Hz for adult listeners, and 1550 Hz for children (Boothroyd, 1968; Boothroyd, 1978).

Though the crossover frequency indicates that half of the information important for speech recognition is contained above this frequency and half below this frequency, it does not necessarily indicate that consonant recognition is 50% correct. In general, removal of half of the acoustic information contained in speech results in only a small decrement in consonant recognition (e.g., Boothroyd, 1978; Miller and Nicely, 1955). The absolute value of this decrement, however, is task-dependent. For example, if the test material is connected discourse (such as sentences or paragraphs), with all of its redundancies, the listener can use contextual cues, resulting in a different weighting of the frequency scale than for recognition of isolated phonemes (i.e., different portions of the frequency scale become more important for perception of connected discourse) (Miller and Nicely, 1955).

The purpose of this paper is to integrate the results of the high-pass and low-pass noise masking studies of this dissertation (Chapters 3, 4 and 5) by examining the contributions of selected frequency regions to behavioral and electrophysiological responses to /ba/ and /da/. The results of the high- and low-pass noise studies will be compared graphically for each behavioral (d' , RT) and event-related potential (ERP) measure (N1, MMN, N2, P3), and crossover frequencies will be determined. To this author's knowledge, this technique has not been used previously with filtered noise masking studies, whether for behavioral or ERP measures of speech recognition.

6C. Method

Chapters 3 and 4 examined the effects of high-pass noise masking on cortical ERPs to speech sounds. Chapter 5 examined the effects of low-pass noise masking on cortical ERPs to speech sounds. The speech sounds examined were /ba/ and /da/ presented as 65 and 80 dB peak-to-peak equivalent (ppe) SPL. Behavioral (d' , RT) and ERP measures (N1, MMN, N2, P3) of speech sound processing were examined. The data from individual subjects in Chapters 3 through 5 were normalized relative to the results of the QUIET condition, and means of these normalizations were obtained. The normalization was performed because it allowed for comparison of different measures (some ERP amplitudes are negative in voltage, and some are positive in voltage; behavioral measures are positive; and the range of the voltage is different for different measures), and because different subjects and parameters were used for some of the studies. For amplitude measures and d' scores, the results were converted into percent of the amplitude or d' value in the related QUIET condition (response strength). Reaction time and ERP latency measures are converted into latency change (ms) from the QUIET condition (latency change). Details of the specific methods can be found in Chapters 3, 4, and 5.

The mean normalized data for each measure were graphed as a function of low-pass and high-pass noise masker cutoff. Crossover frequencies where the curve for high-pass noise results and low-pass noise results intersect were then calculated for each behavioral and ERP measure. For those figures where the curves intersect, the crossover frequency was calculated by performing linear regressions on the high-pass and low-pass noise average results on the data point boundaries around the point of intersection. The frequency represented by the point of intersection, as well as the response strength or latency change from the QUIET condition at the point of intersection, were determined from these linear regression data. For those figures where the high- and low-pass noise masking curves do not intersect, a predicted point of intersection was calculated by extrapolating from the two data points closest to the potential intersection. Two-point linear regressions were performed because they more accurately indicated the actual crossover frequencies than did second or third order polynomial regressions.

6D. Results

Calculations of the crossover frequencies are performed using graphs of response strength and also latency change as a function of high- and low-pass noise masker cutoff frequency. Figure 1 displays these graphs for behavioral and ERP measures of response strength and latency change (see Figure 1).

The results of crossover-point analyses for response strength as a function of high-pass and low-pass noise maskers are displayed in Table 1 for d', N1, MMN, N2 and P3 for speech sounds presented at 65 and 80 dB ppe SPL (see Table 1).

Results of crossover frequency analyses for latency change for RT, N1, MMN, N2 and P3 are displayed in Table 2 (see Table 2).

Specific Data

Response Strength As shown in Figure 1 and Table 1, the crossover frequency is clearly different for N1 compared to the other measures. For 65 dB ppe SPL speech sounds, the N1 crossover frequency is 781 and 891 Hz for /ba/ and /da/, respectively. The crossover frequency is higher for d', MMN, N2 and P3, ranging from 1141 to 1515 Hz. For 80 dB ppe SPL speech sounds, the crossover frequency for N1 is again clearly different from the other measures. In this instance, however, the crossover frequency for N1 is higher (2219 and 1953 Hz for /ba/ and /da/, respectively) than the other measures, which range from 1453 to 1875 Hz.

Response strength at the crossover frequency indicates the strength of neural processing at the frequency where the high- and low-pass noise masking functions intersect. For /ba/ presented at 65 dB ppe SPL, the response strength at the crossover frequency is larger for N1 (87%) compared with the other measures (56 to 66%). This pattern is less clear, however, for /da/ presented at 65 dB ppe SPL. The response strength at the crossover frequency is 84% for N1, compared to d' (57%), N2 (65%), and P3 (73%). The high 93% response strength for the MMN reflects the artificially raised results due to the poor MMN waveforms in the QUIET condition for /da/ for some individual subjects. Their MMNs in QUIET were small in amplitude, and for some of these subjects better waveforms (i.e., higher MMN amplitude and/or lower residual EEG noise) were obtained in

the easier noise masking conditions, resulting in a response strength greater than 100% (Chapter 4). For 80 dB ppe SPL speech sounds, the response strength at the crossover frequency shows no clear pattern of difference between the waves. Response strength varies from 66% to 87%.

The response strength crossover frequency tends to be higher for responses to /da/ compared to responses to /ba/. Exceptions to this pattern occur for N1 and P3, but only for 80-dB speech sounds. The response strength at the crossover frequency tends to be higher for 80-dB speech sounds compared to 65 dB ppe SPL speech sounds. Exceptions to this pattern occur for N1 (/ba/) and P3 (/da/).

Latency Change As shown in Figure 1 and Table 2, the crossover frequency for latency change is clearly different for N1 compared to the other measures. For 65 dB ppe SPL speech sounds, the crossover frequency for N1 is 836 Hz for /ba/ and 820 Hz for /da/. These values are quite different from those obtained for RT, MMN, N2 and P3, which ranged from 1172 to 1671 Hz. For 80 dB ppe SPL speech sounds, the crossover frequency for N1 (750 and 1172 Hz for /ba/ and /da/, respectively) is again lower than the other measures (ranging from 1469 - 1719 Hz). Latency change at the crossover frequency is an indication of the timing of neural processing at the frequency where the high- and low-pass noise masking functions intersect. Examination of latency change at the crossover frequency is clearly patterned. N1 shows the smallest latency change at the crossover frequency (10 - 16 ms), RT, MMN and N2 show larger changes (28 - 88 ms), and P3 shows the largest latency change (91-135 ms).

Across all of the data, the latency change crossover frequency tends to occur at higher masker frequencies for /da/ compared to /ba/. Exceptions to this pattern occur with 65 dB ppe SPL speech sounds for N1, N2 and P3. No clear pattern for latency change at the crossover frequency occurs as a function of speech stimulus. No clear pattern in the crossover frequency for 65 dB ppe SPL speech sounds compared to 80 dB ppe SPL speech sounds is seen. The latency change at the crossover frequency, however, tends to be shorter in response to 80 dB ppe SPL speech sounds than to 65 dB ppe SPL speech sounds, though the pattern of change does not hold for all waves.

Summary Data

65- versus 80-dB Stimulus Intensity With data collapsed across all waves and both stimuli, the crossover frequency for 80 dB ppe SPL stimuli occurs at higher frequencies than for 65 dB ppe SPL stimuli. For response strength, the crossover frequency for 65-dB stimuli is 1216 Hz, and for 80-dB stimuli it is 1705 Hz. The same pattern is seen for latency change, where the crossover frequency for 65-dB stimuli is 1278 Hz, and 1444 Hz for 80-dB stimuli. The response strength at the crossover frequency is slightly higher for 80-dB stimuli (76%) than for 65-dB stimuli (70%). Additionally, the latency change at the crossover frequency is greater for 65-dB stimuli compared to 80-dB stimuli.

Response Strength versus Latency Change With data collapsed across speech stimulus, stimulus intensity, and measure, the crossover frequency is higher for response strength (1433 Hz) compared to latency change (1352 Hz). This difference appears to be due primarily to differences in the crossover frequency for N1 for 80-dB speech sounds. When the data for N1 are excluded, the crossover frequencies for response strength (1425 Hz) and latency change (1482) are similar.

Comparison of Waves The behavioral (d' , RT) and ERP measures (N1, MMN, N2, P3) were compared with data collapsed across speech stimulus and stimulus intensity. For response strength, the differences among the crossover frequencies were small across the measures (d' = 1441 Hz; N1 = 1461 Hz; MMN = 1328 Hz (note: no 80 dB data); N2 = 1481 Hz; P3 = 1403 Hz). The results for N1 are misleading, however, because for 65-dB speech sounds N1 crossover values are lower than the other measures (781-891 Hz); for 80-dB speech sounds, N1 results are higher than the other measures (1953-2219 Hz). When these values are collapsed across stimulus intensity, the mean (1461 Hz) appears similar to those obtained for the other measures. There are some differences in response strength at the crossover frequency. The d' score shows the smallest response strength (64%). MMN, N2 and P3 show larger response strengths (77, 70 and 71%, respectively), and N1 shows the largest response strength (84%).

For latency change, the crossover frequency for N1 is clearly different than for the other measures. N1 has a crossover frequency of 895 Hz, whereas the crossover frequencies for RT (1527 Hz), MMN (1422 Hz, no 80 dB data), N2 (1574 Hz) and P3 (1375 Hz) are clearly higher. There is a progression with wave in the latency change at the crossover frequency. With the exception of MMN, progressively larger changes occur for later/higher-order waves. N1 shows the smallest change (14 ms), N2 shows the next largest change (39 ms), followed by RT (64 ms), MMN (79 ms-no 80 dB data), and P3 (111 ms).

/ba/ versus /da/ Figure 2 (left) displays the response strength and latency change data for /ba/ compared to /da/ (see Figure 2). The data are collapsed across intensity and measure. With data collapsed across all waves and both stimulus intensities, the crossover frequency for /da/ occurs at higher frequencies than for /ba/. For response strength, the mean crossover frequency is 1391 Hz for /ba/, and 1476 Hz for /da/. The same pattern is seen for latency change, where the crossover frequency for /ba/ occurs at 1287 Hz and 1416 Hz for /da/. The response strength at the crossover frequency is higher for /da/ (76%) compared to /ba/ (69%). However, the latency change at the crossover frequency is only slightly greater for /ba/ (62 ms) compared to /da/ (56 ms).

Behavioral versus ERP measures Figure 2 (right) displays the response strength and latency change data for behavioral measures compared to ERP measures. The data are collapsed across stimulus and intensity. ERP results are shown collapsed across all measures (N1, MMN, N2, P3) and also without N1 (MMN, N2 and P3 only). Results for behavioral and ERP measures are very similar, especially without N1. Crossover frequencies for response strength are very close between d' (1441 Hz), all ERP measures (1430 Hz) and ERP measures without N1 (1419 Hz). Response strength at the crossover frequency is 64% for d' , 75% across all ERP measures, and 71% for ERP measures without N1. Crossover frequencies for latency change are also close, with 1527 Hz for RT, and 1464 Hz for ERP measures without N1. The crossover frequency for ERP measures including N1, however, is lower (1301 Hz). Latency change at the crossover frequency is 64 ms for RT, 58 ms across all ERP measures, and 76 ms for ERP measures without N1.

6E. Discussion

/ba/ versus /da/

With the exception of N1, crossover frequencies tended to occur at higher frequencies for responses to /da/ compared to /ba/. This is most likely a ramification of the higher frequency content of the formant transition information required to differentiate /da/ and /ba/. The second formant transition for /da/ in this study was 1800 Hz whereas it was only 1100 Hz for /ba/. The third formant transitions were 2300 and 2500 Hz for /ba/ and /da/, respectively (see Chapter 3, Figure 1). Interestingly, the crossover frequencies for the discriminative measures (behavioral measures, MMN, N2 and P3) all occurred between 1141 and 1875 Hz, all in the approximate region of the second formant transitions. For N1, which is not an indicator of stimulus discrimination (see Chapters 3 - 5), crossover frequencies ranged between 750 and 2219 Hz. This is a much wider range than seen for the discriminative measures, and there is no clear relationship to the speech sounds, except that the speech sounds used for this study contained energy in these frequencies. For example, for 65-dB speech sounds, the N1 crossover frequency in response to /da/ was higher than to /ba/ in terms of response strength, but not for latency change. The opposite effect was seen for 80-dB speech sounds, where the crossover frequency was higher in response to /ba/ than to /da/ in terms of response strength, but not latency change. Therefore, in contrast with the other measures, no clear pattern of the effect of speech stimulus on the crossover frequency occurs for N1. This change with intensity may be due to different weighting of frequency information when speech sounds are amplified. For response strength, high frequencies may become more important for 80-dB speech sounds compared to 65-dB speech sounds, perhaps because second and third formant frequency information is amplified. This argument may also apply for latency change, at least for /da/.

65- versus 80-dB Stimulus Intensity

Crossover frequencies tended to occur at higher frequencies for 80-dB stimuli compared to 65-dB stimuli. At the higher stimulus intensity, the spectral energy required for speech sound discrimination (i.e., formant transitions) is amplified. A higher crossover frequency for the 80-dB

speech stimuli indicates that high frequencies carry more perceptual weight. This suggests that the third formant transitions may become more important to the discrimination of /ba/ and /da/ at the higher stimulus intensity than for the lower stimulus intensity. It is also conceivable that, at the higher stimulus intensity, the formants and formant transitions are less affected by upward spread of the noise masking, which was presented at a constant level, regardless of stimulus intensity. As a result, high frequencies are more audible, and therefore, more important.

Comparison of Waves

Clear differences were seen in the pattern of the results for both response strength and latency change between N1 and the other measures. The crossover frequency for N1 occurred at different frequencies than the other measures (behavioral, MMN, N2, P3). The crossover frequency for N1 response strength was higher in frequency compared with the other measures for 80-dB speech sounds, and lower compared with the other measures for 65-dB speech sounds. The crossover frequency indicates that half of the information important for recognition of speech (in this case, the consonant-vowel syllables /ba/ and /da/) occurs above the crossover frequency and half of the information occurs below the crossover frequency (e.g., Miller and Nicely, 1955). N1 indicates the presence of audible speech stimuli (see Chapter 3). This suggests that for N1 in response to 65 dB ppe SPL speech sounds, for example, half of the information involved in processing the presence of /ba/ and /da/ occurs above about 800 Hz, and half occurs below 800 Hz. It is conceivable that measures of response strength/amplitude at the crossover frequency can be considered indices of the strength of neural processing (Chapters 3 and 4). The response strength at the crossover frequency was larger for N1 than for the other measures. This indicates that it would require more masking in order to break down cortical processing of the *detection* (as indicated by N1) of /ba/ and /da/ than it would for *discrimination* (as indicated by the other measures). Thus, the other measures (as indicated by d', RT, MMN, N2 and P3) are more sensitive to the effects of noise masking. These other measures index discrimination of the speech sounds, and thus information required to discriminate between the speech sounds is more sensitive to the effects of noise masking than is the information that speech sounds are present/audible. This makes sense

acoustically because the spectral information contained in /ba/ and /da/ covers a wide frequency range (see Chapter 3, Figure 1). The sounds are audible if any of this spectral energy is present. The spectral information important for discriminating the speech sounds (i.e., the formant transitions), however, is contained in a limited frequency region. If this information is masked, then it is not possible to discriminate the speech sounds. Therefore, it requires less masking to interfere with speech sound discrimination compared to speech sound presence.

There was a progression in latency change at the crossover frequency for the individual measures such that smallest changes were seen for N1, larger changes were seen for MMN, N2 and RT, and the largest changes were seen for P3. These latency analyses suggest differences at different processing levels within the auditory system. N1 typically occurs approximately 100 ms or more after stimulus onset (e.g., Chapters 3-5; Näätänen and Picton, 1987). The time it takes to process the presence of /ba/ and /da/ was least affected by the masking noise (N1 latency change). MMN and N2 typically occur approximately 200 ms after speech stimulus onset, and RT typically occurs shortly thereafter (e.g., Chapters 3-5; Kurtzberg, Vaughan, Kreuzer and Fliegler, 1995; Kutas, McCarthy and Donchin, 1977; Näätänen, Gaillard and Mäntysalo, 1978). Processing of stimulus discrimination, whether preconscious (MMN) and/or conscious (N2, RT) as indicated by these measures, was more affected by the masking noise. P3 typically occurs approximately 300 ms or more after stimulus onset (e.g., Picton and Hillyard, 1988). It is associated with the psychological significance of stimulus differences (for review, see Picton, 1992). Processing time associated with this wave was most affected by the masking noise. This suggests that P3 reflects additional processing of the speech sounds than do RT and the other measures. This is consistent with the results of Magliero and colleagues (Magliero, Bashore, Coles and Donchin, 1984), who demonstrated that P3 latency in response to visual stimuli presented with visual masking noise reflects stimulus evaluation processes and is relatively independent of processes involved in response selection and execution, such as those underlying RT. Additionally, Kutas and colleagues (Kutas, McCarthy and Donchin, 1977) demonstrated that RT and P3 can be dissociated, and, therefore, these measures can reflect differing functional significance. Kutas and

colleagues proposed that RT reflects processes leading to a cognitive decision and behavioral response, whereas P3 latency reflects the duration of stimulus evaluation processes, including stimulus encoding (and decoding), recognition and classification. They argued that these processes are independent of response selection and execution. It is possible that P3 latency measures contained some overlap from the slow wave (Squires, Squires and Hillyard, 1975). This study, however, used too few electrodes to accurately separate contributions from P3 and the slow wave.

High-Pass versus Low-Pass Noise

There were some differences between the results obtained with high-pass and with low-pass masking. The pattern of results for high- and low-pass noise masking is not always a "mirror image" (see Figures 1 and 2). For example, Figure 2 indicates that with high-pass noise masking, the response strength for /ba/ and /da/ are nearly identical (i.e., the functions overlap). In contrast, with low-pass noise masking, there is a clear difference in the functions for /ba/ and /da/, and the functions do not overlap. This difference is likely caused by greater upward spread of masking seen with low-pass noise masking (e.g., Egan and Hake, 1950). This upward spread of low-pass noise masking would likely influence results for /ba/, with lower frequency formant transitions more than the higher frequency transitions of /da/.

Behavioral versus ERP Measures

It was noteworthy that the crossover frequencies and response strengths at the crossover frequency were similar for both behavioral and ERP measures of discrimination (except for N1, which does not reflect discrimination), indicating these measures provide similar results and assess similar functions. The crossover frequencies obtained from the present studies can be compared to previous behavioral studies. French and Steinberg (1947) reported crossover frequencies of 1700 to 1900 Hz, Miller and Nicely reported a crossover frequency of 1550 Hz (Miller and Nicely, 1955), and Boothroyd reported crossover frequencies of 1550 to 1700 Hz (Boothroyd, 1968; Boothroyd, 1978). These studies all examined the perception of consonants. Miller and Nicely also specifically examined the perception of consonant place of articulation. The crossover

frequency obtained for consonant place alone was 1900 Hz (Miller and Nicely, 1955). The present study found crossover frequencies ranging from 1141 to 1719 Hz for the discriminative measures. Over all measures, the average crossover frequency (1454 Hz) is somewhat lower than those described in the literature. The studies described, however, used filtering of speech, not noise masking of speech. Additionally, those studies were not specific to /ba/ and /da/.

Summary

In summary, crossover frequency analyses indicated differences in the frequency contributions important for discrimination of the two speech sounds used in these dissertation studies (Chapters 3-6). On average, the crossover frequency was higher in response to /da/ compared to /ba/, which is consistent with the frequency composition of the formant transitions differentiating the speech sounds. Additionally, crossover frequencies were higher for responses to 80-dB speech sounds compared to 65-dB speech sounds, perhaps indicating increased contribution of the third formant frequency transition (F3). Crossover frequencies obtained for behavioral measures were remarkably similar to those obtained for ERP measures, with the exception of N1. The crossover frequency for N1 was lower compared with other measures for 65-dB speech sounds, and was higher compared with other measures for 80-dB speech sounds. Moreover, response strength at the crossover frequency was higher for N1 compared to the other measures. There was a progression with wave in latency change at the crossover frequency. Larger latency changes occurred for later waves. These crossover frequency analyses provide more information on neural processing of speech sounds at different processing levels, as well as providing more evidence of differences in the functional significance of ERPs N1, MMN, N2, and P3. Finally, because of the similarity of behavioral and ERP results, these analyses provide further support for the potential clinical utility of ERPs for the populations where behavioral measures of speech sound processing cannot be obtained.

Table 1. Crossover frequencies (Hz) for behavioral (d') and ERP (N1, MMN, N2, P3) measures and response strength (% of the QUIET condition) at the crossover frequency are displayed.

65 dB ppe SPL speech sounds					
	d'	N1	MMN	N2	P3
crossover frequency (Hz)	1328	781	1141	1266	1234
/ba/					
response strength (%)	56	87	60	60	66
crossover frequency (Hz)	1359	891	1515	1328	1313
/da/					
response strength (%)	57	84	93	65	73
80 dB ppe SPL speech sounds					
	d'	N1	MMN	N2	P3
crossover frequency (Hz)	1500	2219	N.A.	1453	1594
/ba/					
response strength (%)	71	80	N.A.	66	72
crossover frequency (Hz)	1578	1953	N.A.	1875	1469
/da/					
response strength (%)	71	86	N.A.	87	72

N.A. = not available

Table 2. Crossover frequencies (Hz) for behavioral (RT) and ERP (N1, MMN, N2, P3) measures and corresponding latency change from QUIET (ms) at the crossover frequency are displayed.

65 dB ppe SPL speech sounds					
	RT	N1	MMN	N2	P3
crossover frequency (Hz)	1234 ^P	836	1359 ^P	1609 ^P	1172 ^P
/ba/					
latency change (ms)	79 ^P	16	70 ^P	39 ^P	135 ^P
crossover frequency (Hz)	1671 ^P	820	1484 ^P	1453 ^P	1141 ^P
/da/					
latency change (ms)	53 ^P	10	88 ^P	40 ^P	114 ^P
80 dB ppe SPL speech sounds					
	RT	N1	MMN	N2	P3
crossover frequency (Hz)	1563	750	N.A.	1594	1469
/ba/					
latency change (ms)	59	13	N.A.	47	102
crossover frequency (Hz)	1640	1172	N.A.	1641	1719
/da/					
latency change (ms)	66	16	N.A.	28	92

^P = predicted by extrapolation

N.A. = not available

Figure Captions

Figure 1: The results of high- versus low-pass noise maskers on behavioral measures (d' , RT) and ERP measures (N1, N2, P3, MMN) are indicated for response strength and latency change as a function of masker cutoff frequency. Responses are shown for 65- and 80-dB speech sounds. Thick lines indicate responses for /ba/, thin lines indicate responses for /da/, and dotted lines indicate predicated data. Crossover frequencies are indicated by intersection of the high- and low-pass noise masking results. The high-pass noise masking results are maximal for response strength and minimal for latency change on the right side of each graph. The low-pass noise masking results are maximal for response strength and minimal for latency change on the left side of each graph. Note that the x axis direction is reversed (going from low frequencies on the right to high frequencies on the left) compared to Chapters 3-5. This was done to facilitate comparison with the behavioral literature concerning crossover frequency.

Figure 2: The results of analyses comparing /ba/ versus /da/ (left) and behavioral measures versus ERP measures (right) are shown for response strength and latency change as a function of noise masker cutoff frequency. For the speech sound comparison (left), responses for /ba/ are indicated by a thick line, and responses for /da/ are indicated by a thin line. For the behavioral versus ERP comparison (right), behavioral measures are indicated by a thick line, ERP measures (N1, MMN, N2, P3) are indicated by a dashed-dotted line, and ERP measures without N1 (MMN, N2, P3) are indicated by a thin line.

Figure 1

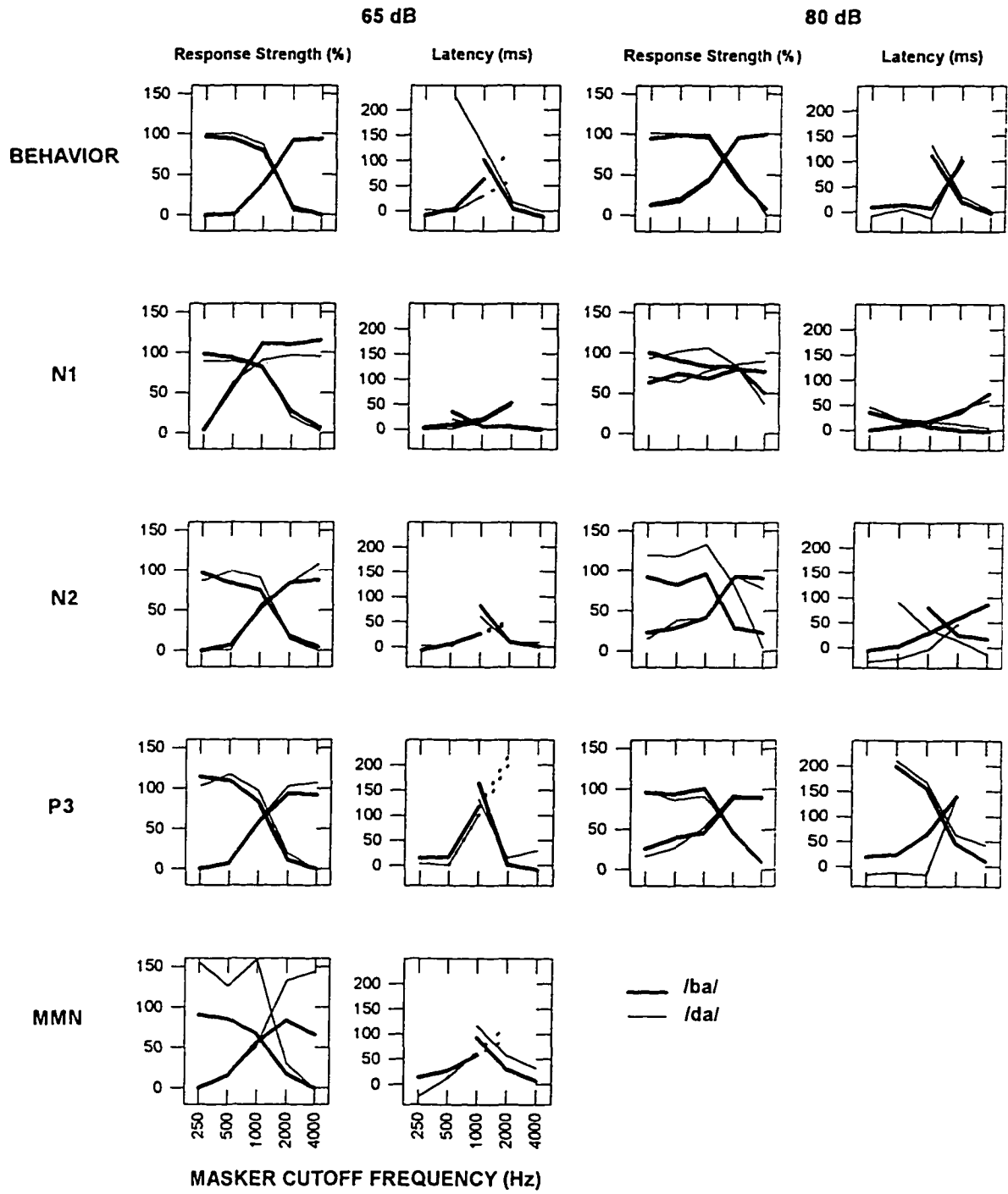
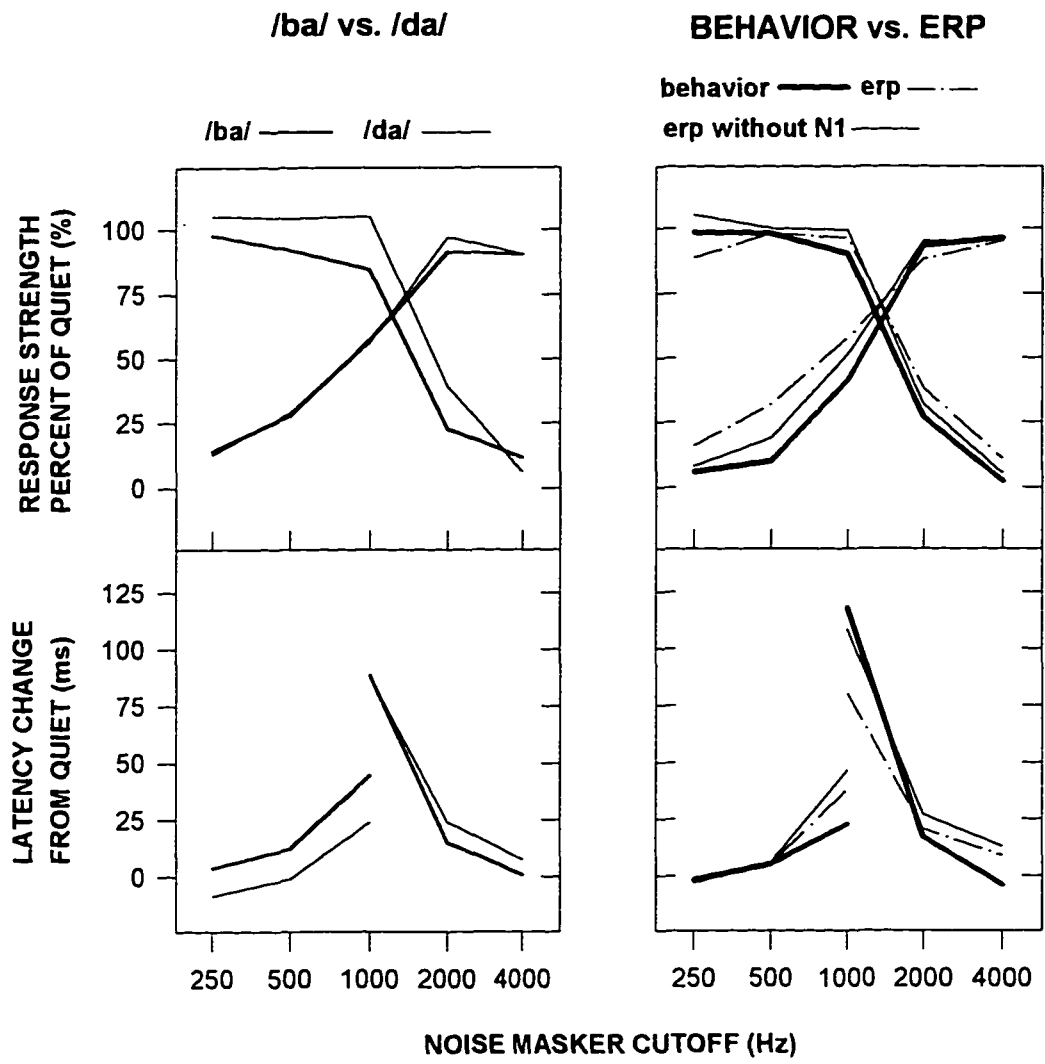


Figure 2



Chapter 7

Summary and Conclusions of the Dissertation

7A. Summary and Conclusions**Spectrally Shaped Noise Masking**

Filtered noise masking was selected for these dissertation studies because it is a more appropriate way to "simulate" sensorineural hearing loss than is use of filtered signals. The threshold elevations produced by masking are predominantly of cochlear origin (e.g., Fletcher, 1953; Humes, Dirks, Bell and Kincaid, 1988), although there may also be cortical contributions to these changes (e.g., Phillips, 1990). Additionally, noise masking results in loudness recruitment that is similar to that seen with sensorineural hearing loss (e.g., Hellman, 1994; Humes, Dirks, Bell and Kincaid, 1988; Humes and Roberts, 1990; Lochner and Burger, 1961; Needleman and Crandell, 1995; Stevens, 1966). Humes and colleagues demonstrated that listeners with simulated hearing loss produced by spectrally shaped noise masking perform similarly to listeners with sensorineural hearing loss on most psychoacoustic tasks involving spectral resolution and speech recognition, with the exception of spectral resolution paradigms involving fixed-level signals. The performance of listeners with simulated hearing loss did not predict well the performance of listeners with sensorineural hearing loss for temporal resolution tasks (Humes, Espinoza-Varas, and Watson, 1988). These findings suggest that use of noise-masked normal listeners is justified for speech perception studies such as the present dissertation studies. Future studies with listeners with sensorineural hearing loss will determine whether the results obtained in this study accurately predict performance with similarly-configured hearing loss.

High-Pass Noise Masking Studies

The use of high-pass noise masking results in decreased audibility for frequencies above the noise masker cutoff. Results of the high-pass noise masking studies (Chapters 3 and 4) indicated that as the cutoff frequency of the high-pass masker was lowered, ERP latencies increased and amplitudes decreased. The cutoff frequency where changes first occurred differed for N1 compared to the MMN, N2, P3 and behavioral performance. N1 showed small changes across

frequency beginning with the 4000-Hz high-pass noise. MMN, N2, P3 and behavioral measures showed large changes that began with the 1000-Hz high-pass noise condition.

Low-Pass Noise Masking Studies

The use of low-pass noise masking results in decreased audibility for frequencies below the noise masker cutoff. Results of the low-pass noise masking studies indicated that as the cutoff frequency of the low-pass noise masker was raised, ERP latencies increased and amplitudes decreased. N1 amplitude showed small decreases for 80-dB speech sounds as the low-pass noise cutoff was raised. For 65-dB speech sounds, N1 showed a more abrupt decrease in amplitude when the low-pass noise masker was raised to 2000 Hz and above, similar to results for MMN, N2 and P3. N1 latency showed small increases as the low-pass noise masker was raised. These increases were smaller than those seen for the other measures, particularly for cutoffs above 1000 Hz. N1 latency changes were different than those seen for the MMN, N2, P3 and behavioral measures, particularly for the 80-dB stimulus intensity. MMN, N2, P3, and behavioral measures showed large changes that occurred when the low-pass noise cutoff was raised to 1000 - 2000 Hz.

Derived Response and Crossover Frequency Analyses

Additional measures in this dissertation demonstrated differences between N1 and the other measures. The derived N1 response (Chapter 4) contained contributions from a broad range of frequencies. In contrast, the derived MMN response showed contributions from center frequencies of 1000 - 500 Hz for /ba/ and 2000 - 500 Hz for /da/. These center frequencies correspond well to the spectral regions important for the discrimination of /ba/ and /da/ (see Chapter 4).

In addition to derived responses, crossover frequency analyses showed differences in the crossover frequency, the response strength at the crossover frequency, and the latency change at the crossover frequency for N1, compared to the other measures.

All of these results indicate that decreased audibility, resulting from the masking, affects N1 differently from MMN, N2, P3 and behavioral measures. N1 reflects the presence of audible stimulus energy. It was therefore present in all conditions where stimuli were audible, whether or

not they were discriminable (Chapters 3-5). MMN, N2, and P3 are present only for those conditions where stimuli were discriminable. Large changes were present for both high-pass and low-pass noise masking studies when the noise maskers included the 1000 - 2000 Hz region (Chapters 3-5). This is the region containing most of the spectral energy differentiating /da/ from /ba/ (i.e., the second formant transition). The pattern of results for behavioral measures was similar to that obtained for the discriminative ERPs (MMN, N2, P3).

7B. Implications

The implications of all the studies (Chapters 3-6) will be considered together. There are implications in terms of brain processing of speech sounds as well as for possible clinical application of these ERPs.

Brain Processing of Speech Sounds At least for /ba/ and /da/, decreased audibility in specific spectral regions results in smaller ERP amplitudes, lower behavioral d' scores, longer ERP latencies, and longer behavioral reaction times. This indicates that decreased audibility resulting from the masking noise alters brain processes associated with the processing of speech sounds. The time required to process the sounds is lengthened, and the strength of the response to the speech sounds is reduced. The maskers affect N1 differently from MMN, N2, P3, or behavioral measures. Studied together, these ERPs permit evaluation of different levels of speech processing within the auditory system.

Cortical ERPs and behavioral measures provide information on the timing, sequence and scalp distribution of brain processing underlying speech perception. N1 is generated in the vicinity of primary auditory cortices (e.g., Näätänen and Picton, 1987; Wolpaw and Penry, 1975). In these studies, mean N1 latencies occurred between 101 and 180 ms after stimulus onset (Chapters 3-5). N1 indexes speech sound audibility, being present when speech sounds are audible, whether or not they are discriminable. The MMN, N2, P3 and behavioral measures assess further processing of the speech sounds associated with speech sound discrimination (Chapters 3-5). These measures occur at longer processing times compared to N1, and have different generators. The MMN is generated in the vicinity of primary auditory cortex (e.g., Alho, 1995; Scherg, Vajsar and

Picton, 1989). In these dissertation studies, mean MMN latencies occurred between 161 and 334 ms after stimulus onset (Chapters 4 and 5). The MMN indexes preconscious speech sound discrimination (Chapters 4 and 5), being present when audible speech sounds are discriminable, whether or not the subject is paying attention. N2, P3 and behavioral measures index conscious speech sound discrimination (Chapters 3 and 5), being present when audible speech sounds are discriminable, but only when the subject is paying attention. In these studies (Chapters 3 to 5), there was a progression in latency of these ERPs. Mean N2 latencies occurred between 217 and 326 ms, RT occurred between 383 and 516 ms, and P3 occurred between 377 and 559 ms. P3 is longer in latency compared to the other measures, and reflects further processing of the speech sounds. Multiple generators contribute to P3 (e.g., Courchesne, 1978; Pritchard, 1981; Vaughan and Ritter, 1970). P3 generators depend somewhat on the specifics of the experimental task, the psychological significance of the task, stimulus modality and response requirements (Pritchard, 1981). Contributions to P3 from frontal cortex (e.g., Courchesne, 1978), centroparietal cortex (e.g., Pritchard, 1981; Vaughan and Ritter, 1970), and auditory cortex (e.g., Richer, Johnson and Beatty, 1983) have been reported.

The information provided by these ERPs is a new tool for examining different stages of speech sound processing. This processing can be broken down into sensory processing (as indexed by N1), pre-attentive discrimination (as indexed by MMN), and task-related conscious discrimination (as indexed by N2 and P3). It has been suggested that N1 indexes the amount of signal information received by the sensory detecting system (Hillyard and Kutas, 1983). Results of these dissertation studies are consistent with this hypothesis. N1 was present when speech sounds were audible. N1 amplitude decreased and latency increased as the amount of sensory information decreased. Thus, N1 amplitude decreased and latency increased when more of the speech stimulus was masked. The MMN automatically indexes a change in auditory sensory information, albeit at a preconscious level (e.g., Näätänen, 1990; Näätänen, 1992). In fact, the MMN has been used as a probe of sensory memory (e.g., Ritter, Deacon, Gomes, Javitt and Vaughan, 1995). Results of these dissertation studies are consistent with automatic processing of a change in

auditory sensory information, because the MMN was present only for conditions where the speech sounds were behaviorally discriminable, and the MMN data were collected while subjects ignored the stimuli. In contrast to N1 and the MMN, studies of N2 and P3 have shown that they index further cognitive processing of the speech sounds, such as recognition and classification, and their psychological significance (e.g., Kutas, McCarthy and Donchin, 1977; Magliero, Bashore, Coles and Donchin, 1984; Picton, 1992). Results of these dissertation studies are consistent with these studies, in that, latency of P3 obtained in these dissertation studies was longer than reaction times. Recognition that the stimuli were different had already occurred (in order for button-press responses to be correct), and therefore, the stimuli were being processed further. Results of these dissertation studies show the importance of audibility in the cognitive processing of speech. N1 is present, even when only minimal amounts of speech sound energy is audible. More specific audible speech sound information was required in order for processing of speech sound discrimination to occur. For these dissertation studies, an audible second formant transition (or partial transition information) was required for discrimination. The MMN automatically indexed this discrimination. N2 and P3 reflected further processing of audible and discriminable speech sound information at a conscious level. In summary, all of these ERPs were affected by changes in audibility, though in different ways.

Clinical Application The results of these dissertation studies have a number of implications for the study of patient populations. First, a high behavioral d' score (or percent correct speech recognition score) does not guarantee that the timing of brain processes related to speech sound processing is unchanged. In some cases, neural slowing occurred before behavioral d' score was affected. For example, in Chapter 5, behavioral d' , MMN, N2 and P3 amplitude changes began with 2000-Hz low-pass noise. In contrast, behavioral RT, MMN, N2 and P3 latency changes began with 1000-Hz low-pass noise. Thus, changes in RT and ERP latency occurred before the behavioral d' score was affected. A change in d' score from 4.65 (100% correct, no false alarm responses) to 4.08 (96% correct, no false alarm responses) is equivalent to only a small change (4%) in percent correct. This change would not normally be considered clinically significant. On

the other hand, a large change in RT might be seen in the presence of a 96-100 percent correct score, which would be important additional information. Such a finding would suggest speech perception difficulty/slowing of speech processing. In the case of a hearing aid fitting, for example, such a finding might indicate that the amplification strategy used was sub-optimal. Typical speech identification tasks currently used in clinical audiology would not be sensitive to these decrements in speech sound processing. Tasks that combine a speech recognition score with a measure of timing (i.e., RT and/or ERP latency) might provide useful additional information (e.g., Whiting *et al.*, submitted). Additionally, ERP measures, which can examine speech sound processing changes both in timing (ERP latency) and in strength (ERP amplitude), may also provide useful additional information. These measures provide information on what happens between the time that stimulus energy is detected (as measured by N1), discriminated at preconscious levels (as measured by MMN), the time that a response to the discrimination is initiated (as measured by RT), and the time that the discrimination is consciously noted and the psychological significance of that stimulus change is processed (as measured by N2 and P3). In addition, ERP measures provide information on the locations within the brain where different levels of processing occur.

Second, ERP measures might be considered for those patients who cannot or will not provide accurate behavioral measures of speech sound audibility and discriminability (e.g., infants, difficult-to-test older patients). N1 may be used to index speech sound audibility. The strong correlations between behavioral performance and discriminative ERPs (MMN, N2, P3) suggest that these "discriminative" ERPs may be used to index speech sound discrimination. If a MMN is elicited, then evidence suggests the brain was able to differentiate, at a cortical level, between two speech sounds. There are, however, some limitations to these measures which will be addressed below ("limitations of the dissertation studies").

N1 and MMN may prove to be particularly useful for difficult-to-test populations with hearing loss. Electrophysiologic measures may be the only information available on an infant's hearing. Reliable measures of hearing threshold using behavioral methods cannot be obtained until an infant is *at least* 5-6 months of age (Gravel, 1989). Additionally, neurological disorders and

behavioral problems can make it difficult to obtain reliable measures of hearing sensitivity in some older children (Northern and Downs, 1984). It is difficult to obtain behavioral measures of speech discrimination abilities in these patients (e.g., Gravel, 1994). Hearing aid fittings on these patients, therefore, are sometimes based on very limited information. The goal of amplification is to make as many as possible of the spectral cues important for speech perception audible (e.g., Seewald, Ross and Spiro, 1985). It may be difficult to obtain measures of which cues are being provided. Auditory brainstem response (ABR) measures can be used to obtain reliable and frequency-specific estimates of hearing sensitivity in these difficult-to-test populations (e.g., Stapells, Gravel and Martin, 1995), however, they do not directly assess suprathreshold abilities such as speech perception. Cortical auditory ERPs may provide a way to obtain these measures, and therefore may provide us with more information on the effectiveness of amplification, and provide ways to monitor changes with amplification and therapy.

The results seen with decreased audibility due to the noise masking should be applicable to patients with peripheral hearing loss. The masked audiograms produced by the high-pass maskers are similar to those seen with moderate high-frequency sensorineural hearing loss. The masked audiograms produced by the low-pass noise maskers are similar to those seen with moderate low-frequency hearing loss. Results of the dissertation studies (Chapters 3 - 5) suggest that even moderate hearing loss produces slowing of brain processes and decreases in the strength of those processes involved in the evaluation of speech stimuli. This alteration in brain processing of the speech sounds conceivably could result in difficulties with speech perception.

The acoustic cues differentiating certain speech sounds are not always available to hearing-impaired listeners. The cues may be degraded, distorted, or completely inaudible. The present study provides more information on changes in neural processing that occur when acoustic cues are clearly audible (e.g., QUIET condition), degraded (e.g., 1000-2000 Hz masker conditions), or inaudible (e.g., BBN condition). When acoustic cues differentiating /ba/ from /da/ were degraded using noise masking, subjects took longer to process the speech sounds, and the strength of processing was reduced. It is likely that persons with hearing loss may show similar changes in

neural processing. If true, ERPs may be used to examine these changes and to examine the extent to which amplification remediates these changes. Further research examining changes in neural processing with hearing loss and with amplification are clearly needed.

7C. Limitations of the Dissertation Studies for Clinical Application

There are some limitations in terms of the implications of this dissertation. First, the results are somewhat limited to the CV syllables /ba/ and /da/, and specifically, the tokens used for the dissertation studies. Different results would likely be obtained for /ba/ and /da/ with different frequency composition (for example from a female talker compared to a male talker), and different results would likely be obtained for other speech sounds. However, it is expected that the overall findings that N1 shows a different pattern of results compared to MMN, N2, P3 and behavioral measures would be unchanged with different stimuli. In addition, the differences seen with changes in intensity (65 compared to 80 dB speech sounds) would likely remain. The relationship of the discriminative ERPs to behavioral measures also would be unchanged.

Some of the results of this study may also be limited to populations where /ba/ and /da/ contrasts are native to the language. For clinical populations, it is necessary to know whether brain processing of these speech sounds is altered when the sounds are not native to the patient. For example, if one uses a speech contrast that is not part of the patient's repertoire, one cannot know if absence of a P3 is due to an absence of the acoustic cues necessary for the discrimination or whether it is due to the patient's language.

Results may be different if the stimuli are not presented as isolated speech tokens. Evaluation of speech in more natural contexts (words, sentences, running speech) is needed. Measures of speech perception obtained in such a highly constrained manner may not truly represent speech perception ability in real-world environments. Listeners normally have additional cues with which to work, such as knowledge of the topic of conversation, speech reading cues, coarticulation, etc..

The types of tasks required to elicit the ERPs (i.e., oddball paradigm, slow rate of presentation, need for multiple trials, etc.) also limits the potential clinical application of these ERPs. Procedures that are appropriate for a laboratory setting may not be realistic in a clinical setting.

Several studies have demonstrated that there is considerable variation in the cortical ERPs, particularly for infants and children. These variations include problems with response presence, changes with sleep state, and rapid changes in waveform morphology with development (e.g., Kurtzberg, 1989; Kurtzberg, Hilpert, Kreuzer and Vaughan, 1984; Kurtzberg, Vaughan, Kreuzer and Fliegler, 1995). Further limitations for clinical application include the tradeoff between the number of sweeps needed for optimal signal-to-noise ratios for the recordings, and the amount of time that a clinical patient can be tested. This is particularly true for young children and difficult-to-test populations. Obtaining ERP measures is time-consuming, and techniques for shortening the testing process need to be developed. It is therefore important to prioritize the information considered critical to obtain.

Further limitations for clinical application are that N2 and P3 require the subject to pay attention to the sounds and to count or press a button to the deviant sounds. This is not possible for all subject populations, particularly those that we would most like to assess using these potentials. Infants do not show "P3", but do show P3-like cortical discriminative potentials (Kurtzberg, 1989). These responses are later and are different in morphology than P3. The MMN may provide an alternative index that the brain has differentiated between two speech sounds at a cortical level. The MMN does not require subjects to pay attention, and it can be elicited in infants and young children (e.g., Alho, Saino, Sajaniemi, Reinikainen and Näätänen, 1990; Cheour-Luhtanen, Alho, Kujala, Sääo, Reinikainen, Renlund, Aaltonen, Eerola and Näätänen, 1995; Kraus, McGee, Micco, Sharma, Carrell and Nicol, 1993). Despite these limitations for clinical application, it remains likely that those patients that can be tested would show a similar overall pattern of results compared to those obtained in the dissertation studies (Chapter 3 - 5). It is also conceivable that because attention is not required in order to elicit the MMN, that the MMN may provide a more sensitive indication of discriminative abilities of infants and young children compared to the behavioral techniques used to date (i.e., head-turn responses, non-nutritive sucking, measures, heart-rate measures, etc.).

These dissertation studies were carried out on normal-hearing listeners. Although masking is frequently used to "simulate" hearing loss, use of noise-masked normal listeners is not the same as studying listeners with physiological hearing loss (sensorineural, conductive, mixed). Studies examining the effects of degree and configuration of hearing loss on cortical ERPs are needed in order to determine whether similar results are obtained. Additionally, studies examining the effects of unilateral *versus* bilateral hearing loss have not yet been done. An additional area of investigation is the effects of amplification on these ERPs. It would be interesting to know whether amplification affects all of the ERPs, or only some of the ERPs, and exactly how the ERPs change with amplification.

7D. Future Studies

Despite the limitations of the dissertation, the data obtained are nevertheless quite useful. The studies are the first to demonstrate the effects of decreased audibility for specific spectral regions on the cortical auditory ERPs N1, MMN, N2, and P3, as well as their relationship to behavioral measures d' and RT. This work leads directly to potential investigations in the following areas: 1) The effects of decreased audibility for specific spectral regions produced by sensorineural, conductive, or mixed hearing loss; 2) ERP measures of the effectiveness of amplification by examination of changes in amplitude and latency with hearing aids or cochlear implants; 3) Examination of plastic brain changes with amplification and/or training; 4) Examination of neural changes produced by transient hearing loss (i.e., deprivation effects of otitis media); 5) Further examination of suprathreshold auditory capabilities of infants, and developmental changes in these abilities; and 6) Examination of neural changes in populations where hearing loss is likely, such as the aged.

Appendix of ANOVA Tables

Abbreviations

d.f.	degrees of freedom (unadjusted)
q	Greenhouse-Geisser epsilon adjustment for d.f.
S.S.	sums of squares
M.S.	mean squares
F	ANOVA F value
p	probability (after d.f. adjustment, if applicable)

The following pages contain ANOVA tables for the primary amplitude and latency analyses in this dissertation. These analyses are organized according to chapter. Not all of the ANOVAs performed in the dissertation are contained in this appendix, as the number of these analyses and secondary analyses is quite large. The ANOVA data are also contained within the text of this dissertation.

Chapter 3

d'

<u>source of variance</u>	<u>d.f.</u>	<u>p</u>	<u>S.S.</u>	<u>M.S.</u>	<u>F</u>	<u>p</u>
speech stimulus	1		0.198	0.198	1.82	.210
error	9		0.979	0.109		
stimulus intensity	1		6.520	6.520	14.40	.004
error	9		4.075	0.453		
condition	7	.473	1119.6	159.94	428.96	.000
error	63		23.59	0.373		
S x I	1		.085	.085	1.40	.268
error	9		0.549	0.061		
S x C	7	.341	.618	.088	.86	.457
error	63		6.498	.103		
I x C	7	.370	4.06	.581	2.77	.071
error	63		13.204	.209		
S x I x C	7	.482	.199	.029	.32	.833
error	63		5.62	.089		

Chapter 3

RT

<u>source of variance</u>	<u>d.f.</u>	<u>η</u>	<u>S.S.</u>	<u>M.S.</u>	<u>F</u>	<u>p</u>
speech stimulus	1		5638.80	5638.80	2.07	.200
error	6		16346	2724.46		
stimulus intensity	1		2431.94	2431.94	.47	.520
error	6		31298	5216.47		
condition	4	.489	299736	74934.2	32.38	.000
error	24		55543	2314.31		
S x I	1		353.61	353.61	.24	.641
error	6		8808.05	1468.01		
S x C	4	.466	1283.08	320.77	.42	.651
error	24		18178	757.45		
I x C	4	.612	3659.72	914.93	.48	.666
error	24		45940	1914.17		
S x I x C	1	.482	.199	.029	.32	.833
error	6		11438	476.61		

Chapter 3

N1 Amplitude

<u>source of variance</u>	<u>d.f.</u>	<u>p</u>	<u>S.S.</u>	<u>M.S.</u>	<u>F</u>	<u>p</u>
speech stimulus	1		.040	.040	.04	.839
error	9		8.24	.915		
stimulus intensity	1		32.39	32.39	18.36	.002
error	9		15.88	1.76		
condition	7	.361	323.76	46.25	15.24	.000
error	63		191.19	3.03		
S x I	1		.232	.232	.19	.672
error	9		10.87	1.21		
S x C	7	.560	.74	.11	.21	.927
error	63		31.41	.498		
I x C	7	.339	87.74	12.53	6.41	.005
error	63		123.25	1.96		
S x I x C	1	.409	6.43	.919	1.34	.245
error	9		43.06	.684		

Chapter 3

N1 Latency

<u>source of variance</u>	<u>d.f.</u>	<u>p</u>	<u>S.S.</u>	<u>M.S.</u>	<u>F</u>	<u>p</u>
speech stimulus	1		829.55	829.55	36.69	.000
error	8		321.87	35.76		
stimulus intensity	1		2578.53	2578.53	13.72	.006
error	8		1128.66	125.41		
condition	5	.409	18769.4	3753.89	31.50	.000
error	40		2786.65	77.41		
S x I	1		28.97	28.97	.18	.680
error	8		1134.15	126.02		
S x C	5	.524	412.15	82.43	2.16	.078
error	40		1267.15	35.20		
I x C	5	.580	351.94	70.39	.79	.563
error	40		2403.52	66.76		
S x I x C	1	.416	956.46	191.29	2.09	.153
error	8		2326.61	64.63		

Chapter 3

N2 Amplitude

<u>source of variance</u>	<u>d.f.</u>	<u>Q</u>	<u>S.S.</u>	<u>M.S.</u>	<u>F</u>	<u>p</u>
speech stimulus	1		5.36	5.36	2.41	.155
error	9		19.96	2.22		
stimulus intensity	1		16.75	16.75	1.72	.222
error	9		87.48	9.72		
condition	7	.202	2142.43	306.06	20.18	.000
error	63		955.60	15.17		
S x I	1		15.63	15.63	4.41	.065
error	9		31.95	3.55		
S x C	7	.488	17.17	2.45	.50	.709
error	63		309.94	4.92		
I x C	7	.461	70.04	10.01	2.06	.123
error	63		305.62	4.85		
S x I x C	7	.482	17.68	2.53	.92	.450
error	63		172.16	2.73		

Chapter 3

N2 Latency

<u>source of variance</u>	<u>d.f.</u>	<u>η</u>	<u>S.S.</u>	<u>M.S.</u>	<u>F</u>	<u>p</u>
speech stimulus	1		2555.20	2555.20	2.98	.128
error	7		6004.39	857.77		
stimulus intensity	1		901.5	901.5	.85	.387
error	7		7427.53	1061.07		
condition	4	.530	98912	24728	16.77	.000
error	28		41294	1474.79		
S x I	1		2616.31	2616.31	1.96	.204
error	7		9320.82	1331.55		
S x C	4	.433	8739.43	2184.85	2.04	.116
error	28		29991	1071.13		
I x C	4	.587	1505.81	376.45	.58	.682
error	28		18277	652.77		
S x I x C	1	.417	1975.13	493.78	.31	.703
error	7		44782	1599.39		

Chapter 3

P3 Amplitude

<u>source of variance</u>	<u>d.f.</u>	<u>ρ</u>	<u>S.S.</u>	<u>M.S.</u>	<u>F</u>	<u>p</u>
speech stimulus	1		4.57	4.57	.97	.350
error	9		51.43	5.71		
stimulus intensity	1		237.57	237.57	10.65	.009
error	9		197.88	21.99		
condition	7	.413	6007.73	858.25	49.07	.000
error	63		813.97	12.92		
S x I	1		2.61	2.61	.48	.506
error	9		74.66	8.30		
S x C	7	.381	68.10	9.73	2.05	.139
error	63		460.59	7.31		
I x C	7	.423	88.49	12.64	2.27	.105
error	63		610.12	9.68		
S x I x C	7	.498	15.18	2.17	.56	.673
error	63		394.31	6.26		

Chapter 3

P3 Latency

<u>source of variance</u>	<u>d.f.</u>	<u>Q</u>	<u>S.S.</u>	<u>M.S.</u>	<u>F</u>	<u>p</u>
speech stimulus	1		11344	11344	1.59	.243
error	8		57079	7134.91		
stimulus intensity	1		59.63	59.63	.02	.882
error	8		20274	2534.36		
condition	4	.554	594004	148501	45.04	.000
error	32		105504	3297.02		
S x I	1		35.20	35.20	.02	.902
error	8		17541	2192.68		
S x C	4	.411	12703	3175.94	.72	.481
error	32		141959	4436.25		
I x C	4	.569	18925	4731.38	2.28	.125
error	32		66268	2070.89		
S x I x C	4	.682	6344.39	1586.09	1.37	.277
error	32		36923	1153.85		

Chapter 4

d'

<u>source of variance</u>	<u>d.f.</u>	<u>ρ</u>	<u>S.S.</u>	<u>M.S.</u>	<u>F</u>	<u>p</u>
speech stimulus	1		.122	.122	1.09	.322
error	10		1.12	.111		
condition	6	.430	617.70	102.93	435.44	.000
error	60		14.18	.236		
S x C	6	.500	.711	.118	2.41	.086
error	60		2.95	.049		

RT

<u>source of variance</u>	<u>d.f.</u>	<u>ρ</u>	<u>S.S.</u>	<u>M.S.</u>	<u>F</u>	<u>p</u>
speech stimulus	1		391.03	391.03	.25	.627
error	10		15562	1556.21		
condition	3	.393	371995	123998	45.00	.000
error	30		82667	2755.57		
S x C	3	.581	3186.96	1062.32	1.71	.212
error	30		18664	622.15		

Chapter 4

N1 Amplitude

<u>source of variance</u>	<u>d.f.</u>	<u>p</u>	<u>S.S.</u>	<u>M.S.</u>	<u>F</u>	<u>p</u>
speech stimulus	1		3.21	3.21	11.11	.008
error	10		2.89	.289		
condition	6	.288	114.32	19.05	16.52	.000
error	60		69.22	1.15		
S x C	6	.490	1.19	.199	1.07	.374
error	60		11.10	.185		

N1 Latency

<u>source of variance</u>	<u>d.f.</u>	<u>p</u>	<u>S.S.</u>	<u>M.S.</u>	<u>F</u>	<u>p</u>
speech stimulus	1		346.10	346.10	12.14	.006
error	10		285.15	28.52		
condition	4	.698	12466	3116.66	76.86	.000
error	40		1622.10	40.55		
S x C	4	.465	230.17	57.54	1.64	.184
error	40		1404.99	35.12		

Chapter 4

Peak-MMN Amplitude

<u>source of variance</u>	<u>d.f.</u>	<u>p</u>	<u>S.S.</u>	<u>M.S.</u>	<u>F</u>	<u>p</u>
speech stimulus	1		.573	.573	.93	.359
error	10		6.18	.618		
condition	6	.480	104.69	22.85	17.45	.000
error	60		45.81	.764		
S x C	6	.477	6.81	1.13	1.77	.177
error	60		38.43	.640		

Peak-MMN Latency

<u>source of variance</u>	<u>d.f.</u>	<u>p</u>	<u>S.S.</u>	<u>M.S.</u>	<u>F</u>	<u>p</u>
speech stimulus	1		653.78	654.78	.30	.615
error	4		37183	3718		
condition	3	.594	89096	29698	10.03	.001
error	12		41511	2075		
S x C	3	.626	9299.92	774.99	1.24	.340
error	12		27734	1386		

Chapter 4

Mean-MMN Amplitude

<u>source of variance</u>	<u>d.f.</u>	<u>Q</u>	<u>S.S.</u>	<u>M.S.</u>	<u>F</u>	<u>p</u>
speech stimulus	1		.245	.245	.50	.456
error	10		4.34	.434		
condition	6	.563	32.95	5.98	5.49	.000
error	60		66.76	1.11		
S x C	6	.579	3.03	.504	.46	.834
error	60		73.06	1.22		

Chapter 5

d

<u>source of variance</u>	<u>d.f.</u>	<u>ρ</u>	<u>S.S.</u>	<u>M.S.</u>	<u>F</u>	<u>p</u>
speech stimulus	1		.386	.386	3.72	.086
error	9		.933	.014		
stimulus intensity	1		17.22	17.22	31.98	.000
error	9		4.85	.538		
condition	6	.296	1040.24	173.37	299.49	.000
error	54		31.26	.579		
S x I	1		.475	.475	10.97	.009
error	9		.390	.043		
S x C	6	.446	1.30	.216	1.84	.170
error	54		6.34	.117		
I x C	6	.341	24.30	7.72	4.05	.004
error	54		28.31	.524		
S x I x C	6	.507	1.40	.233	4.27	.013
error	54		2.95	.055		

Chapter 5

RT

<u>source of variance</u>	<u>d.f.</u>	<u>p</u>	<u>S.S.</u>	<u>M.S.</u>	<u>F</u>	<u>p</u>
speech stimulus	1		5096.31	5096.31	7.87	.021
error	9		5831	647.96		
stimulus intensity	1		15741	15741	5.57	.043
error	9		25453	2828.11		
condition	3	.438	14839	4946.51	2.16	.167
error	27		61971	2295.22		
S x I	1		84.10	84.10	.46	.516
error	9		1653	183.75		
S x C	3	.727	4490.61	1496.87	4.58	.021
error	27		8831	327.11		
I x C	3	.557	22669	7556.43	7.23	.008
error	27		28233	1045.67		
S x I x C	3	.683	2187.72	729.24	2.22	.136
error	27		8852	327.86		

Chapter 5

N1 Amplitude

<u>source of variance</u>	<u>d.f.</u>	<u>Q</u>	<u>S.S.</u>	<u>M.S.</u>	<u>F</u>	<u>p</u>
speech stimulus	1		.046	.046	.03	.872
error	9		15.27	1.70		
stimulus intensity	1		34.95	34.95	18.32	.002
error	9		17.17	1.91		
condition	6	.318	466.47	77.75	34.34	.000
error	54		122.25	2.26		
S x I	1		.021	.021	.04	.844
error	9		4.66	.518		
S x C	6	.485	5.29	.881	1.16	.343
error	54		41.02	.759		
I x C	6	.449	49.04	8.17	8.00	.001
error	54		55.19	1.02		
S x I x C	6	.516	2.04	.341	.70	.563
error	54		26.21	.485		

Chapter 5

N1 Latency

<u>source of variance</u>	<u>d.f.</u>	<u>p</u>	<u>S.S.</u>	<u>M.S.</u>	<u>F</u>	<u>p</u>
speech stimulus	1		2121.02	2121.02	26.31	.007
error	4		322.47	80.62		
stimulus intensity	1		2743.93	2743.93	31.96	.005
error	4		343.46	85.87		
condition	4	.380	35804	8951.20	78.91	.000
error	16		1814.97	113.44		
S x I	1		239.27	239.27	12.12	.025
error	4		78.99	19.75		
S x C	4	.425	121.31	30.33	.40	.654
error	16		1215	75.98		
I x C	4	.322	1661.31	415.33	3.72	.107
error	16		1784	111.55		
S x I x C	4	.289	279.50	69.88	1.45	.296
error	16		772.61	48.29		

Chapter 5

N2 Amplitude

<u>source of variance</u>	<u>d.f.</u>	<u>ρ</u>	<u>S.S.</u>	<u>M.S.</u>	<u>F</u>	<u>p</u>
speech stimulus	1		.101	.101	.01	.924
error	9		98.89	10.54		
stimulus intensity	1		131.27	131.27	11.94	.007
error	9		98.98	10.99		
condition	6	.269	4848.89	808.15	28.17	.000
error	54		1549	28.69		
S x I	1		.009	.009	0.00	.954
error	9		21.93	2.44		
S x C	6	.615	91.12	15.19	2.35	.079
error	54		349.59	6.47		
I x C	6	.451	110.34	18.39	1.61	.216
error	54		617.76	11.44		
S x I x C	6	.530	68.34	11.39	2.05	.127
error	54		300.43	5.56		

Chapter 5

N2 Latency

<u>source of variance</u>	<u>d.f.</u>	<u>p</u>	<u>S.S.</u>	<u>M.S.</u>	<u>F</u>	<u>p</u>
speech stimulus	1		11458	11458	72.0	.000
error	4		1432	159		
stimulus intensity	1		534.02	534.02	.51	.495
error	4		9511	1056		
condition	3	.571	19837	6612.34	6.42	.012
error	27		27788	1029		
S x I	1		202.09	202.09	.42	.532
error	4		4307	478		
S x C	3	.543	1511.03	503.68	1.68	.220
error	16		8078	299		
I x C	3	.424	1581.29	527.09	.69	.456
error	27		20488	758		
S x I x C	3	.593	1835.78	611.93	2.40	.127
error	27		6878	254		

Chapter 5

P3 Amplitude

<u>source of variance</u>	<u>d.f.</u>	<u>p</u>	<u>S.S.</u>	<u>M.S.</u>	<u>F</u>	<u>p</u>
speech stimulus	1		55.80	55.80	5.43	.045
error	9		92.49	10.28		
stimulus intensity	1		179.91	179.91	4.19	.071
error	9		386	42.97		
condition	6	.325	8660.17	1443.36	41.73	.000
error	54		1867	34.58		
S x I	1		.385	3.85	.57	.47
error	9		60.83	6.76		
S x C	6	.479	33.47	5.58	.79	.506
error	54		381	7.07		
I x C	6	.548	207.24	34.54	2.60	.066
error	54		717	13.29		
S x I x C	6	.610	36.17	6.03	1.62	.195
error	54		200	3.71		

Chapter 5

P3 Latency

<u>source of variance</u>	<u>d.f.</u>	<u>η</u>	<u>S.S.</u>	<u>M.S.</u>	<u>F</u>	<u>p</u>
speech stimulus	1		7930.66	7930.66	4.96	.053
error	9		14398	1599		
stimulus intensity	1		18084	18084	3.90	.080
error	9		41719	4635		
condition	3	.535	115450	38483	9.71	.003
error	27		106987	3962		
S x I	1		2.93	2.93	0.00	.967
error	9		14156	1572		
S x C	3	.607	11647	3882.40	1.95	.176
error	27		53812	1993		
I x C	3	.626	50842	16947	3.87	.044
error	27		118292	4381		
S x I x C	3	.661	5148.93	1716.31	1.33	.290
error	27		34930	1293		

Chapter 5

Peak-MMN Amplitude

<u>source of variance</u>	<u>d.f.</u>	<u>p</u>	<u>S.S.</u>	<u>M.S.</u>	<u>F</u>	<u>p</u>
speech stimulus	1		5.27	5.27	2.40	.156
error	9		19.76	2.19		
stimulus intensity	1		6.72	6.72	4.59	.061
error	9		13.17	1.46		
condition	6	.390	266.40	44.40	36.03	.000
error	54		66.54	1.23		
S x I	1		.154	.154	.33	.579
error	9		4.19	.465		
S x C	6	.415	4.79	.799	.71	.532
error	54		60.86	1.13		
I x C	6	.523	6.54	1.09	1.58	.214
error	54		37.18	.689		
S x I x C	6	.338	5.89	.982	2.37	.121
error	54		22.37	.414		

Chapter 5

Peak-MMN Latency

<u>source of variance</u>	<u>d.f.</u>	<u>η</u>	<u>S.S.</u>	<u>M.S.</u>	<u>F</u>	<u>p</u>
speech stimulus	1		27351	27351	14.60	.007
error	7		13118	1874		
stimulus intensity	1		10280	10280	3.15	.119
error	7		22882	3268		
condition	3	.599	57227	19075	10.26	.003
error	21		39032	1858		
S x I	1		993.52	993.52	1.10	.328
error	7		6298	899		
S x C	3	.576	20378	3792.70	4.03	.050
error	21		35394	6792		
I x C	3	.543	9074.85	3024.95	.92	.41
error	21		69331	3301		
S x I x C	3	.681	2166.99	722.33	.62	.556
error	21		24577	1170		

Chapter 5

Mean-MMN Amplitude

<u>source of variance</u>	<u>d.f.</u>	<u>p</u>	<u>S.S.</u>	<u>M.S.</u>	<u>F</u>	<u>p</u>
speech stimulus	1		2.02	2.02	.54	.481
error	9		33.74	3.75		
stimulus intensity	1		1.54	1.54	1.92	.199
error	9		7.26	.806		
condition	6	.476	57.8	9.64	8.41	.000
error	54		61.89	1.15		
S x I	1		.052	.052	.06	.819
error	9		8.41	.934		
S x C	6	.580	1.93	.32	.31	.93
error	54		56.13	1.04		
I x C	6	.498	5.59	.93	1.19	.328
error	54		42.41	.785		
S x I x C	6	.579	5.06	.844	1.08	.372
error	54		42.28	.783		

Chapter 8

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