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**Laryngeal and aerodynamic management of consonantal voicing
distinctions in men, women, and children**

by
Laura L. Koenig

A dissertation
submitted to the Graduate Faculty of Speech and Hearing Sciences
in partial fulfillment of the requirements
for the degree of Doctor of Philosophy

The City University of New York

1998

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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 requirements for the degree of Doctor of Philosophy.

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Abstract
**Laryngeal and aerodynamic management of
consonantal voicing distinctions in men, women, and children**

by
Laura L. Koenig
Advisor: Katherine S. Harris

Voiceless consonant production has traditionally been measured by means of voice onset time (VOT) and discussed in terms of interarticulator timing. More generally, however, voicing involves management of subglottal pressure and details of laryngeal setting, and many of these factors undergo developmental change. Mechanical and aerodynamic conditions at the glottis may therefore show considerable variation in normal populations as functions of age and/or sex. This study considers whether consonantal voicing control may vary across populations in ways consistent with known group differences in laryngeal and aerodynamic parameters. Intraoral pressure, oral airflow and acoustic signals were collected from English-speaking men, women and 5-year-old children producing voiceless stops and /h/, and measures were made of voice onset time, /h/ voicing and flow characteristics, subglottal pressure, and f_0 . Clear age and gender effects are observed for /h/: Fully-voiced /h/ is most common in men, and /h/ voicing break durations show the widest range of values among the 5-year-olds. Parallel trends are observed in the stop VOT data. This suggests that developmental change in VOT reflects, in part, mastery of voicing itself, and also that subtle differences in voicing behavior may exist between men and women. Correlations among /h/ voicing, flow, pressure and f_0 performed across and within subjects reveal both group patterns and individual variation, providing further support for the hypothesis that speakers adopt individual strategies for achieving voicing distinctions in accord with the physical conditions defined by their production systems.

in memory of SVE and GLK

Acknowledgments

I would like to break with usual practice here by giving my acknowledgments in forward, rather than reverse, chronological order on the grounds that starting from the present and working back through my life implies a certain finality or last word to this document and I cannot imagine that it is either of those things; I quite hope it is not. Those wishing to read about the contributions of my committee members and current colleagues will therefore need to flip ahead a few pages.

I would like to begin by acknowledging the major forces in my prehistory:

my mother, a woman of strong character and industriousness;

my father, a man of subtle creativity and strong beliefs, who carried a great weight with him and never chose his words lightly;

my early mentors: Shirley Von Ehr, Eva Ebers, Alice Giesler, and Kevin Briggs, who offered me challenges, security, and possibilities.

From Chicago, where I came of age, I remember the following:

the extended Room 200 community: Mary Bartholomew, Mike Novak, Sallie P. Skyles, Verna McQuown, Jan Dorsey, Mary Jean Kraybill, Andy Walters, Bronis deSupinski, Diane Durante, Jennifer Cully Shaw, Sharon Rosen, Agnes Zellner, Alma Williams, Chris Anderson, Tom Ryan, Kate Chesley, Larry Arbeiter, Ellen McGrew, Carol Peterson, Robert Ashenhurst, Jonathan Kleinbard, Geoffrey C. M. Plampin and John Plampin;

Samuel Rebelsky, Dwayne Paul, David Ijaz, Heidi Cuesta, Paul Rohr, Joe Bernstein, Charles Louise, for the company they provided;

Pamela D. Hodgson, for her uniqueness of character;

Norman, Ruth, David and Michael Lebovitz, who were for two years my family downstairs;

Bill Murphy, Lamar Riley Murphy, Debbie Gillaspie, and Frederick Sturm for their advice and support.

Among the university faculty I am grateful to

Karl Joachim Weintraub, for his wisdom, honesty, perceptiveness, and those 7 am conversations;

J. David Greenstone, for his humanity, enthusiasm and intellect;

Ralph Walter Johnson, for encouragement out of nowhere ;

Isaac D. Abella, for his energy and dedication;
 David Bevington, for fostering a wide academic community;
 Karen Landahl, for introducing me to the field of phonetics and giving it
 ambitious coverage;
 Kostas Kazazis and Christina von Nolcken for their time and breadth of interests;
 Victor H. Yngve, for his visionary spirit and intellectual idealism;
 John Goldsmith, James D. McCawley, and Jerry Sadock, for being astute and
 talented linguists.

I credit the Linguistics Department faculty of the University of Pennsylvania for
 teaching me how to collect and work with data. I would like to express specific
 appreciation to:

Sherry Ash, for sharing her wide technical expertise;
 George Cardona and Don Ringe, for their good will and skills of observation;
 John Fought, for doing more than anyone else to train my phonetic ear;
 Lila Gleitman and Michael Kelly of the Psychology Department, for turning their
 interest in linguistic issues into tangible activities and resources;
 Mary Jack, Myrna Schwartz and colleagues at the Moss Rehabilitation Center, for
 introducing me to clinical data;
 Richard D. Janda, for being open-minded and generous with his time and energy
 Bill Labov, for giving me access to and experience with his vast store of speech
 data, and for being a fountain of provocative ideas and comments;
 Mark Liberman, for his technical contributions to the department during my last
 year of residency and for his role in developing databases and means of access to
 linguistic data;
 Saul Sternberg, for his combination of enthusiasm and sharp intellect.

Gratitude also to Nicola Bessell, Christine Zeller, and Tom Veatch for their camaraderie
 and companionship, and to Derek Davis, Erin Davis, Linda White, and Suzanne
 Schneider Ross for providing a wider Philadelphia community.

Leigh Lisker and Arthur Abramson deserve credit for many things, but above all I am
 grateful to them for giving me the opportunity to work with them at Haskins Labs early
 during my years at Penn. My academic career has been shaped very strongly by my
 association with the Labs; I value my history there and feel fortunate to be a member of
 the Haskins community. While I cannot begin to catalogue the names of all Lab

associates I have enjoyed and learned from, I would like to give recognition to the following (in no principled order): Fredericka Bell-Berti, Bryan Gick, Simon Levy, Margaret Hall Dunn, Bruno H. Repp, Rena Krakow, Ignatious Mattingly, Qi Wang, Louis Goldstein, Doug Honorof, Elliot Saltzman, Doug Whalen, Ram Frost, Ken Pugh, H. Betty Kollia, Dorothy Ross, Michele Sancier, Philip Rubin, Mark Tiede, Robert Remez, Bill Scully, and Yvonne Manning-Jones. Special thanks to Alice Faber and Melanie Campbell for the assistance they gave me in recording my child subjects; and to Anders Löfqvist, Vince Gracco and Carol Fowler for making my research assistantship possible.

My compliments to the proprietors of Aladdin's Middle Eastern Food, Mom's Indian Food, BAR, and Atticus Bookstore cafe for providing me with various forms of material subsistence during my extended sojourns in New Haven.

From the years immediately leading up to this thesis I would like to express appreciation to the following:

the faculty and staff in the Department of Speech and Hearing Sciences at the CUNY Graduate School for the rich and multifaceted environment they have provided, and especially to the Irving Hochberg for the many ways he has facilitated my graduate student career;

the members of the Speech and Theater Department at Lehman College, CUNY, especially Martin Gitterman, Lawrence Raphael, Robert Goldfarb, and Nora Roback, for their support and encouragement;

my colleagues at Long Island University, Brooklyn, for their patience and enthusiasm during recent months;

my students from both institutions, for helping me remember how much I still believe in education;

Now to the matter directly at hand:

I owe a great debt to Richard S. McGowan for his support and involvement during the early stages of this project. Although professional developments eventually took him elsewhere, Richard's thinking remains evident in many ways in this work. What understanding I have of speech aerodynamics is due primarily to his teaching.

Richard Schwartz has been a positive and pragmatic influence on my work throughout my time at CUNY. His chief contributions to this project have been to remind me of the larger issues of linguistics and development that underlie any work

on children's speech, and, perhaps even more importantly, to help me believe that I could actually run an experiment involving 5-year-olds.

It has been a privilege to have had input and advice from Anders Löfqvist on this and many other projects during my time at Haskins. I have tremendous respect for Anders as a scientist and researcher, and I hope I can emulate his standards.

Katherine Harris has played a strong and complex role in my work and life over the past several years. It was because of her encouragement that I applied to the Graduate School, and she has done much to keep me in the program and the field. I suspect I may be somewhat atypical among her students in various ways, but nevertheless I am honored to count myself as part of her legacy. Along with reading several early drafts of this document, she provided indispensable guidance at a number of critical phases in this project, and I am deeply, personally grateful.

Elaine Stathopoulos, who generously served as my outside reader, made a number of useful suggestions and observations which have improved this work.

Ken Pugh ventured boldly out of psychology into the wilds of speech production to offer inquisitive comments from a more general audience.

Don Kennison was my proofreader *par excellence*. Any errors that remain now reflect my own last-minute editing.

I hope I have made good use of the advice and assistance I have received from all of these people.

I end by acknowledging my friends of recent years. Thanks to:

Frank A. Petito, for keeping me alive;

Elizabeth Mishler, the extended Guggenheim crew—Steve DeRiseis, Simone Manwaring, Linda Hunsaker Hardman, Sue McGuire, Lauriston Avery, John Parks Graz, Erik Davidovicz and Phaedra Caffrey Davidowicz—and the cast and crew of *Fingerprints* and *Mirror my eyes, my window*, for ongoing intellectual and artistic stimulation;

James M. Knipfel, and his family, George and Janice Knipfel, and Mary, Bob, McKenzie and Jordan Adrians for the support they have offered over the past several years.

And now it's time to get on with things.

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0. Introduction

Normal speech production requires the ability to make a variety of laryngeal adjustments both quickly and finely. During vowels and other voiced sounds, speakers must achieve and maintain laryngeal postures and transglottal pressures appropriate for sustained oscillation. To make consonantal voicing distinctions, they must manipulate air pressure levels below and above the larynx, and coordinate abduction and adduction movements with oral closures and constrictions. The phonetic literature on speech acquisition indicates that adult-like laryngeal control takes years to develop. Not only must children learn the details of laryngeal setting and timing, but they must do this within a context of ongoing change in the structural and aerodynamic properties of their sound-producing mechanism. In the larynx, this process is further complicated by secondary sexual differentiation that affects males in particular and contributes significantly to the well-known gender differences in voice pitch and quality in adults.

Direct data on laryngeal structure and activity during speech remain relatively sparse. The larynx is difficult to access through noninvasive methods, and, composed largely of soft tissues, it images poorly, undergoes deformation and positional variation during routine activity, and is subject to shrinkage and stiffening when excised. Histological and imaging studies are almost invariably cross-sectional and suffer chronically from small sample sizes, making it difficult to detect subtle group differences, and the typical practice of averaging across individuals may obscure details of growth patterns. In light of such problems, speech researchers have made extensive use of indirect data. Acoustic and aerodynamic measures of voice quality have been analyzed for possible

indications of vocal pathology and differences in laryngeal structure and setting between adult men and women; age-related decreases in fundamental frequency have been taken as a metric of laryngeal descent and growth; and the acoustic manifestations of consonantal voicing patterns have been used to infer the timing between laryngeal and supralaryngeal events.

Consonantal voicing has been approached in the phonetic literature primarily through studies of voice onset time (VOT) in initial stops in stressed syllables. VOT, defined as the time between consonantal release and the onset of voicing, is understood to indicate the relative timing between laryngeal and oral activities. The developmental literature has shown that children attain adult-like VOT patterns at a fairly late age, particularly in the case of voiceless aspirated stops. The usual explanation for this has been that the voiceless aspirates are “difficult” insofar as they require fine temporal coordination between laryngeal and supralaryngeal articulators.

More precisely speaking, however, interarticulator phasing is only one of a number of factors involved in producing conditions at the glottis appropriate for voicing. Other relevant parameters include the extent of glottal ad/abduction, the shape of the glottal channel, the transglottal pressure, and vocal fold tissue characteristics including tension. Especially when looking across speaker groups, these other parameters cannot be entirely neglected, because they are known to vary systematically with speaker sex and age. Work on voice quality in men and women has long acknowledged the possible roles of these other factors. The underlying question in the current study is whether they may play a role in distinctive voicing control as well.

The work reported here follows in the vein of a number of recent studies by analyzing aerodynamic data for information about laryngeal activity in running speech. Specifically, oral airflow, intraoral pressure, and acoustic signals were collected from normal American English-speaking men, women, and 5-year-old children and used to investigate characteristics of abduction gestures and consonantal voicing patterns. The low-frequency (DC) variation in oral flow around /h/ is taken as an index of the glottal abduction maneuver, and peak pressure during /p/ is taken as an index of subglottal pressure for the utterance. Voice onset time is measured for the stops and a roughly analogous measure, VOT_h, is defined for voicing breaks associated with /h/. Finally, glottal pulse (AC) amplitude and f_0 are measured around /h/ to obtain more information about vocal fold vibratory characteristics in the vicinity of an abduction maneuver.

As expected, the data show some age differences in VOT distributions for the voiceless aspirated stops: Namely, measures of VOT variability are significantly higher in the children than the adults. In addition, there are hints of a gender effect in adults, with slightly shorter VOTs in men than women. Both age and gender effects are seen clearly in the voicing patterns around /h/ and are largely interpretable in terms of structural differences in the larynx across populations. Correspondences between subjects' voicing patterns for the stops and in /h/, especially marked for the children, support the claim that /h/ voicing can be an important source of information on voicing behavior in an individual, and indicate that control of voicing itself must account for some of the variability in children's aspirated stop VOTs. Thus, developmental changes in VOT cannot be interpreted purely in terms of improving interarticulator timing skill. The greater prevalence of voiced /h/ in men than in women suggests further that

distinctive voicing control may be influenced by the same kinds of laryngeal factors that contribute to gender differences in voice quality in adults.

Correlational analyses of /h/ voicing, subglottal pressure, flow rates, and f_0 performed across and within subjects show some group patterning and also a fair amount of individual variation in the interrelationships among the several parameters involved in voicing control. These results have general implications for the assessment of vocal function in male and female speakers of all ages, and expand the range of observations for which descriptions of consonantal voicing control and its acquisition in children must account.

-

1. Literature review

1.0 Overview

In order to address the issue of population differences in laryngeal function for speech, it is necessary to consider several bodies of literature. Since measures of voicing onset constitute a major component of the data collected in this study, this chapter begins with a review of the traditional voice onset time (hereafter VOT) work on adults, and the developmental studies of VOT in English-speaking children. To provide a basis for discussing how structural and aerodynamic differences among groups may affect voicing control, summaries are then given of the physical requirements for voicing and of developmental changes in relevant laryngeal and respiratory parameters. Considerable variation in voice quality has been documented among speaker groups as functions of age and gender,¹ and standard interpretations of this variation draw heavily on physical differences in laryngeal structure and aerodynamic quantities. The review of this literature is intended to provide a model for discussing the group differences in voicing patterns observed in the current data. The most extensive variation here is observed during /h/ production; accordingly, the chapter ends with a brief phonetic characterization of /h/.

1.1 Voice onset time and voicing of stop consonants

In their classic study, Lisker and Abramson (1964) found that, within a number of languages, contrastively-voiced stop consonants showed distinct VOT distribu-

¹ Throughout this text, I will use the term 'gender' where causes could conceivably include sociological or cultural factors, and reserve 'sex' for cases where physical factors appear to be solely responsible.

tions, and that, across languages, one could identify three basic categories:

1) Negative VOT, characterized by voicing before the time of oral release (i.e., during the consonantal closure). This is the (pre)voiced case. 2) Short-lag or zero (0) VOT, with voicing beginning at or very shortly after the time of release.

These are the voiceless inaspirates. 3) Long-lag or positive VOT, where a longer delay, usually accompanied by aspiration noise, follows closure release. These are the voiceless aspirates. American English is generally said to distinguish between voiceless aspirated and unaspirated stops in syllable-initial, prestress position, with the complication that the voiceless inaspirates may alternate with voiced closure intervals in some speakers and phonetic contexts. Syllable-initial stops have received most attention in studies of children's speech and are likewise the focus of interest below. Voicing distinctions in other environments have different articulatory and acoustic characteristics and will not be considered here.

An extensive literature exists on age-correlated changes in VOTs, especially for English-speaking children. Preliminary studies of naturalistic speech from subjects as young as 6 months (Preston & Yeni-Komshian 1967; Preston et al. 1968) showed a preponderance of short-lag stops in children from both American-English and Lebanese-Arabic environments (the Arabic system contrasts voiced stops with voiceless inaspirates). Long-lag stops began to occur more frequently in English-learning children around age 2. In a more detailed discussion of apical stops in 3 American children, Kewley-Port and Preston (1974) noted that children's mean VOTs for /t/ remained short compared to adults' well after bimodal (contrastive) /d, t/ distributions had been established, as late as 4.5 years. Inspection of Kewley-Port and Preston's histograms reveals that although most of the children's /t/'s fell in the short-lag range, there were a

few outliers with very long VOTs. Zlatin and Koenigsnecht (1976) similarly found short means and skewed distributions for /p, t, k/ in 2- and 6-year-olds; indeed, Zlatin's adult data (1974) showed certain patterns of skew as well.

The occurrence of marked skew in VOT data may be relevant to interpreting the conclusions of Macken and Barton (1980). Based on results from children up to 4 years of age, these authors proposed a 3-step developmental sequence for English-learning children: First was a stage of unimodal VOT distributions in the short-lag range. Secondly, bimodal distributions developed, but averages for the voiceless aspirates remained short. Stage three was marked by adult-like mean values for long-lag stops. Some children appeared to reach mature values by first "overshooting" (producing very long values) and later shortening back to adult values. Barton and Macken (1980) found consistently longer VOT means in 4-year-olds than adults in both isolated words and in running speech, and took this as further evidence for an overshoot phase in acquiring voiceless aspirates. Other authors have reported long VOT means in children's aspirated stops as well. Gilbert (1977) measured a small sample of /t/'s from 2- to 3-year-olds and observed many VOTs >110 msec. Menyuk and Klatt (1975) noted some VOTs of 200+msec in 3- to 4-year-olds. Smith (1978) also found longer VOT averages for /t/ in 2- and 4-year-olds than adults.

Although several studies report VOT values for older children, no consensus has been reached on later developmental trends. Eguchi and Hirsh (1969) recorded children ages 3 to 13 repeating two short sentences. Mean VOT values did not undergo systematic change over time, but the voiceless stops did show a steady decrease in intra-subject variability up to about age 8. Kent and Forner (1980) measured a variety of durations in 4-, 6-, and 12-year-old's and adult subjects'

productions of three sentences, including VOT means and standard deviations (SDs) for word-initial /k/ and /t/ in *cat* and *took*, respectively. For /k/, but not /t/, means and SDs declined with age among the child groups. Coefficients of variation ($\text{CoV} = \text{SD} / \text{mean}$) showed a marked drop after 4 years of age. A study of speech kinematics by Ostry et al. (1984) included VOT measures for 11 children, 3;3-11;6, producing /g/ and /k/ in nonsense disyllables. Age-related trends in means are not evident, but the authors reported a decrease in variability with age. Inspection of their data reveals that two subjects, ages 3;11 and 5;6, were largely responsible for this apparent age effect. Finally, Ohde (1985) recorded nonsense monosyllables from 8- to 9-year-olds and measured VOTs along with post-release f_0 values. For all categories, but especially for the voiceless aspirates, the children showed longer mean VOTs than adults, and higher SDs, but comparable CoVs.

Many aspects of these data remain unexplained, but most researchers concur that short-lag stops are the norm in young children, and that voiceless aspirates are later developments. Most have also accepted Kewley-Port and Preston's (1974) explanation for this pattern. Following studies (Lisker et al. 1970; Sawashima et al. 1970) showing much cross-speaker and cross-token variation in the occurrence of abduction for short-lag stops, Kewley-Port and Preston argued that voiceless unaspirated stops were prevalent in young children because they could be achieved in a variety of ways. Namely, an increase in intraoral pressure may suppress voicing even with the vocal folds adducted, and, when abduction does occur, similar acoustic results will obtain so long as the vocal folds have returned to a fairly well-adducted state by the time of release. Fully-voiced and long-lag stops have more stringent production requirements: The former may require active maneuvers to increase supraglottal volume and maintain a transglottal

pressure drop (cf. Bell-Berti 1975; Bickley & Stevens 1986; Müller 1983; Westbury 1983), and in the latter the abduction-adduction gesture must coincide precisely with oral release to yield a period of aspiration. The voiceless aspirated category has thus been seen as a particular test of articulatory timing skill. Although there have been some recent attempts to account for developmental VOT patterns in terms of phonological feature complexity (e.g., Tyler & Edwards 1993; Tyler & Saxman 1991) or perceptual salience (Davis 1995), in general the notion has persisted that the developmental progression of voiceless aspirated stops reflects primarily improved skill in laryngeal-supralaryngeal timing, and that ongoing variability in children's aspirated VOTs should be interpreted in terms of interarticulator timing control. --

Reports of age-related decreases in VOT variability have played an important role in the debate over why children's speech often shows higher intra-subject variability than adults'. One complication that arises in this context is that absolute variability tends to correlate with the magnitude of what is being measured, so that greater standard deviations in children may arise simply as an artifact of the longer durations they typically show (cf. Kent & Forner 1980; Ohala 1975; Rimac & Smith 1984; Smith 1978; Smith 1994). Studies evaluating this possibility have generally concluded that greater durations may contribute to children's variability but do not account for it entirely. Durational effects also cannot account for findings of increased variability in children's kinematic and postural measures (e.g., Sharkey & Folkins 1985; Smith 1995; Watkin & Fromm 1984). Researchers have usually relied on the coefficient of variation to normalize durational effects in their data. But the CoV is inappropriate for comparing VOT measures across voicing categories, since mean values range from negative to positive. For voiceless inaspirates (with mean values around 0), CoVs may be

extremely high or simply undefined. Thus, VOT presents certain issues of methodology and interpretation that do not arise for many other types of speech durational measures.

Moreover, the developmental VOT work has tacitly assumed that differences across speakers in VOT values may arise only as a result of variations in relative timing between laryngeal abduction and articulatory release. In particular, it has been assumed that laryngeal abduction and its effects on voicing constitute an invariant event that is comparable across speakers, and can only be shifted in time. This assumption deserves closer scrutiny. It is certainly true that, within an individual speaker, all else being equal, variations in articulator phasing can be expected to have a direct effect on VOT, and this is clearly one of the critical parameters that speakers manipulate in producing VOT contrasts. But when comparing across different speaker populations, all else is not equal, and it becomes necessary to evaluate VOT data within the broader context of what is known about achieving phonation under various vocal tract conditions. The next section briefly reviews the factors relevant to a larger discussion of voicing control.

1.2 Physical requirements for voicing

At least since the time of van den Berg (1958), it has been widely accepted that sustained laryngeal vibration is principally achieved by establishing appropriate aerodynamic and mechanical conditions at the glottis. To do this, speakers manipulate the translaryngeal pressure differential, the extent of laryngeal ad/abduction, and vocal-fold length and stiffness. These parameters are interdependent, so that the range of allowable values for one depends to some extent

on the current settings of the others. For example, the minimum transglottal pressure required for vocal-fold oscillation has been estimated to be about 2–3 cm H₂O in adults (Bickley & Stevens 1986). Threshold pressures to the lower end of an individual's range may be used under conditions of smaller glottal widths; slacker, thicker folds; and/or lower vocal-fold viscosity (Stevens 1977; Titze 1994; cf. also Ishizaka & Flanagan 1972).

The aerodynamic requirements for speech are often stated in terms of subglottal pressure. This formulation is fairly accurate during vowel production in normal speakers, where the upper vocal tract is relatively unconstricted and pressure above the larynx is close to atmospheric. It ceases to be valid when airflow is obstructed, as in stop consonant production (Warren 1982). In running speech, intraoral pressure behind a stop closure typically rises quickly, equalizing sub- and supraglottal pressure and suppressing voicing as the translaryngeal pressure differential approaches 0. The general equation relating translaryngeal pressure to volume flow and glottal area is

(eq. 1)	$\Delta P = k_t \rho U^2 / 2A^2 = k_t \rho u^2$ (Ishizaka & Flanagan 1972)
where	k_t is an empirically-derivable coefficient that depends closely on glottal geometry, especially area,
	ρ is the air density (a constant),
	U is translaryngeal volume flow,
	A is the minimum area in the glottis,
and	u is the particle velocity of air within the glottis.

The k_t factor becomes an issue when comparing pressure and flows across widely varying glottal areas. Measurements by Scherer and Guo (1991) for a highly simplified rectangular model of the glottis show little change in k_t with changing cross-sectional areas above .05 cm². Below this value, decreasing area yields rapidly increasing k_t . Calculations using available normative data and a

simple triangular glottis (see Appendix A) suggest that $.05 \text{ cm}^2$ is somewhat smaller than what may be expected during abduction in a 5-year-old.

Accordingly, we will tentatively assume comparable k_t across subject groups below.

The minimum pressure drop across the glottis that will permit oscillation, the phonation threshold pressure, P_{th} , has been formalized for the two-mass model of the vocal folds (discussed below) as

(eq. 2) $P_{th} = cBx_0k_t/T$ (Ishizaka & Flanagan 1972;
see also Titze 1988)

where c represents the coupling stiffness (in more detailed physiological models, this parameter largely reflects the settings of the laryngeal muscles, especially the cricothyroid and the vocalis),
 B is the damping within laryngeal tissues,
 x_0 is prephonatory glottal half-width (i.e., the extent of ad/abduction),
 k_t is the translaryngeal pressure coefficient,

and T is the thickness of the vocal folds.

The factors c , T , and x_0 represent aspects of laryngeal setting which are partially under a speaker's control; B is determined by tissue viscosity; and k_t represents the aerodynamic conditions in the vicinity of the glottis. According to this equation, phonation threshold pressure varies linearly with stiffness, damping, glottal half-width, and the pressure coefficient, and is inversely related to T .

In the two-mass model, each vocal fold is represented as a pair of coupled masses in the vertical dimension. When the masses are not coupled too tightly, they can vibrate out of phase with each other so that cross-sectional area and, correspondingly, intraglottal pressure will vary as a function of height. (In this context, the term "glottal area" is usually understood to mean the average width

from the lower to the upper margins of the folds.) Self-sustaining oscillation is made possible by a constant interplay between the intraglottal pressure and the restoring forces of the two masses over the course of the vibratory cycle (cf. Stevens 1977; 1988). Much laryngeal research in subsequent years has been directed toward describing these vertical phase differences and their effects on the phonation threshold pressure. Titze (1988) derives the pressure requirements for oscillation under conditions of a time-varying vertical margin as:

$$(eq. 3) \quad PL \geq 2cBk_t/T * [(\xi_{01} + \bar{\xi})^2 / (\xi_{01} + \xi_{02} + 2\bar{\xi})]$$

where

$\bar{\xi}$ is the static mean tissue displacement,

ξ_{01} and ξ_{02} are the time-varying measures of actual glottal width at the bottom and top margins of the glottis, respectively,

and

the phonation threshold pressure is defined by the equality.

This formulation implies that the extent to which the glottis converges or diverges from bottom to top (the glottal convergence angle) is also a relevant factor in determining voicing behavior. Subsequent studies have confirmed that phonation threshold pressures are lower for a convergent glottis (a rest configuration in which $\xi_{01} > \xi_{02}$) than for a divergent one, and when the degree of coupling between the masses allows for a substantial vibratory phase difference between lower and upper masses (e.g., Bickley 1991; Lucero 1993, 1996a; Titze 1994). Some models have also begun to incorporate anterior-posterior variation in glottal area and to simulate effects of incomplete closure of the vocal folds, either resulting from slight abduction or from a “chink” between the arytenoids (Cranen & Schroeter 1995, 1996; Pelorson et al. 1994; Titze 1984). These improvements in laryngeal modeling have made it possible to achieve a broader range of phonatory behaviors and, in some cases, a closer match to the

behavior of human speakers. They have also pointed up some of the limitations on our knowledge of the larynx. For example, some work suggests that vocal-fold tissue characteristics such as viscosity and the intrinsic stress of the vocal folds differ as functions of age and physiological condition (Finkelhor et al. 1988; Titze 1994; Verdolini et al. 1994). Yet information on the mechanical properties of vocal-fold tissues in children is virtually nonexistent, and many of the values used in standard adult models are open to question as they are derived from canine larynges or from measurements made elsewhere in the human body where viscous conditions may be quite different from those in the vocal fold (Titze & Talkin 1979). Although researchers have begun to recognize that men's and women's voices may require different sets of parameter values, mathematical and modeling studies aimed at clarifying and quantifying the relationships among factors involved in voicing control nevertheless often incorporate best-guess values for adult male speakers (Lucero 1996b; Titze & Talkin 1979; Westbury & Keating 1986). At the same time, few experimental studies have addressed the factors determining voicing offsets and onsets in live speakers, and these have not begun to sample across age and sex.

Thus, although the theoretical requirements for sustained oscillation have been laid out in reasonable detail, the range of values available to and used by normal speakers has not been well delimited. It is clear, however, that a full discussion of consonantal voicing control must refer to a number of factors in addition to the timing of ab/adduction gestures. These include at least the following: Sub- and intraglottal pressure levels, tissue characteristics, muscle use patterns, and cross-sectional glottal area, both at its minimum and as it changes throughout the depth of the glottis. Although we lack precise information on how many of these factors vary across speakers, the direct data on structural and aerodynamic

factors suggest that substantial cross-population differences may exist. The next two sections summarize the literature on laryngeal structure and aerodynamic quantities in normal male and female speakers of varying ages.

1.3 Developmental effects on the larynx

During childhood, dramatic changes occur in the position of the laryngeal complex relative to supralaryngeal structures, and in the positioning of the hyoid bone and the laryngeal cartilages relative to each other (for details, see Bosma 1975; Crelin 1973, 1987; Goldstein 1980; Lieberman 1984; Sasaki et al. 1977).

Vocal-fold length appears to increase in a roughly linear fashion through about 12 years, at least in girls; young boys may show comparable trends (Hirano et al. 1983) or may experience two separate growth spurts (Goldstein 1980). Other major changes during the first few years of life include development of the vocal ligament and exponential thinning of the outer mucosal layer of the vocal folds. Not until adolescence does one observe fully differentiated deep tissue layers and an adult-like ratio of vocal-fold thickness to length. Some changes in viscosity and muscle fiber organization may continue into adulthood (Kahane 1982).

Although minor aspects of sexual dimorphism may begin to appear at young ages (Crelin 1973), the major male-female differences in the larynx result from pubertal changes in males. Kahane (1982) measured excised prepubertal and pubertal larynges from both sexes. In his data, cartilage lengths and weights, especially for the thyroid cartilage, increased with age in both sexes, but boys showed 2 to 3 times more growth than girls. Before puberty, vocal-fold length was approximately equal in boys and girls (mean difference = .04mm), but lengths were about 25% greater for pubertal and adult males than females. Titze

(1989) used measurements from Kahane (1982) and Hirano et al. (1983) to quantify the differences between adult male and female larynges. On average, the vocal folds are longer, thicker, and slacker (i.e., less stiff) in men than in women. All of these factors combine to yield lower average fundamental frequencies in men than women, a generalization that holds across languages despite considerable inter-subject variation in both groups (for a recent summary, see Pagaroro-Krook, 1988). The stiffness difference has to do with the fact that vocal-fold growth occurs mainly in the membranous region, both during early development and in adolescent males, so that the proportion of cartilaginous tissue within the vocal fold is lowest in adult men. Higher stiffnesses among female and child speakers can yield decreased dynamic ranges in addition to higher f_0 's. (For theoretical discussion, see Stevens 1977; for some empirical evidence of reduced dynamic profiles in children, see McAllister et al. 1994.) The effect of greater vocal-fold length in men is primarily to allow greater lateral amplitude of vocal-fold vibration. Finally, added mass may create bulging glottal margins in men, making them less likely to have a posterior "chink" between the arytenoids during normal phonation (Titze 1989). Direct observation of the larynx confirms that a glottal chink is typical in women, but less so in men (Bless et al. 1986 as cited in Klatt & Klatt 1990; Södersten & Lindestad 1990), although the precise gap configuration in women may show some age effects (Lineville 1992). Some of the gender differences in voice quality and aerodynamic parameters discussed below probably result in part from this variation in glottal shape.

1.4 Group differences in respiratory and aerodynamic measures

Throughout childhood and into adolescence, measures of lung volume and capacity increase as roughly linear functions of height. Outward recoil pressure

of the lungs rises and expiratory flow rates increase well into the teenage years, for speech and non-speech tasks (Bernthal & Beukelman 1978; de Troyer et al. 1978; Hoit et al. 1990; Mansell et al. 1977; Netsell et al. 1994; Polgar & Weng 1979; Stathopoulos & Weismer 1985a, b; Trullinger & Emanuel 1983). At the same time, subglottal and intraoral pressures decrease (Bernthal & Beukelman 1978; Netsell et al. 1994; Stathopoulos 1995; Stathopoulos & Weismer 1985b). Since pressure and flow are directly related via the laryngeal resistance (flow \times resistance = pressure), the combination of low flows and high pressures in children is usually attributed to increased resistance, afforded by generally smaller passageways throughout the lower airways, the larynx, and the upper vocal tract (Stathopoulos & Weismer 1985a, 1985b; Trullinger & Emanuel 1983).

In general, the patterns of flow and pressure variation during speech are comparable in children and adults; thus, for example, voiceless stops usually show higher intraoral pressure buildups and higher flows on release than voiced stops for subjects of all ages (e.g., Bernthal & Beukelman 1978; Stathopoulos & Weismer 1985b; Trullinger & Emanuel 1983). Yet certain aspects of airflow management for speech do vary as a function of age. Preadolescent children may be more likely than adults to expire below their resting expiratory levels during speech, and/or less likely than adults to inspire to higher lung volumes for more demanding speech tasks (Russell & Stathopoulos 1988; Stathopoulos & Sapienza 1993b; Stathopoulos & Sapienza 1997). Hoit et al. (1990) found that children used relatively more rib cage displacement than adults to increase lung volume, and Netsell et al. (1994) estimated that preschool children must rely largely on expiratory muscle activity during speech, in contrast to adults who use both inspiratory and expiratory muscle force. Stathopoulos and her co-authors have also suggested that children tend to use laryngeal adjustments during intensity variation,

whereas adults rely more on respiratory adjustments (Stathopoulos & Sapienza 1993b).

In contrast to age effects, sex effects in respiratory system variables are relatively small for both children and adults, and can be largely attributed to body size differences (Polgar & Weng 1979; Hoit et al. 1990; Stathopoulos & Sapienza 1997 also speculate that small gender effects in children might result from boys using higher speaking volumes than girls). Men and women expend approximately equal percentages of their vital capacities during reading passages, and show similar responses to increased flow and intensity requirements (Russell & Stathopoulos 1988; Stathopoulos & Sapienza 1993a). Indirect measures of subglottal pressure during speech have generally not shown significant sex effects, and where effects do appear they are inconsistent across studies. Where gender differences have been found in adults is in airflow: On average, expiratory flow rates are somewhat higher for men than women (Polgar & Weng 1979). Flow rates during speech may show more marked effects depending on the type of event measured. Stathopoulos and Weismer (1985a) found no gender effect on peak flows following release of /t/ and /d/ in varying positions and stress contexts, while Stathopoulos and Weismer (1985b) found significantly higher peak flows for voiceless consonants in monosyllables in men than in women, but no difference for 4- to 12-year-old girls and boys. Lower peak flows in females have generally been attributed to increased laryngeal airway resistance resulting from smaller average glottal areas (Holmberg et al. 1988; Stathopoulos & Weismer 1985b). Since shape factors also affect resistance (see, e.g., Titze 1994), some differences in glottal geometry may also be indicated. Higher AC airflows, or pulse amplitudes, have also been found in men as compared to women or child subjects (Löfqvist et al. 1995; Stathopoulos & Sapienza 1993b). The AC flow is the

airflow modulation that occurs with every glottal pulse, and is an index of the amplitude of vocal-fold vibration. Increased vocal-fold length in men allows greater amplitude of vibration, and is probably responsible for their greater average AC flows.

In short, the anatomical and aerodynamic literature provides evidence for age- and sex-related variation along virtually all the dimensions that affect sustained vocal-fold oscillation during running speech. Differences may include vocal-fold length, thickness, internal composition (and probably mechanical properties as a result); aspects of glottal shape; airflow rates; air pressures; and air supplies for speech. A sizable body of literature indicates that vibratory characteristics do, in fact, vary across populations in predictable ways based on these anatomical and aerodynamic differences. These characteristics have usually been discussed under the heading of voice quality.

1.5 Studies of voice quality and voice source features

1.5.1 Suprasegmental variation

Although some studies have analyzed linguistically distinctive uses of voice quality (e.g., Ladefoged 1983; Ren 1992), more work has been carried out in languages where voice quality carries affective or prosodic information. A major goal of this literature has been to relate perceptually defined characteristics of normal and pathological voices with features of the standard acoustic signal and/or indirectly obtained laryngeal signals including inverse-filtered acoustics, airflow, or EGG. For normal voices, one of the most well-established results has been that breathy voice qualities are more often observed in women than men.

The characteristics of breathy voices may include the following: A strong first harmonic component; damping of F1 (or increased F1 bandwidth); subglottal resonances and/or antiresonances; faster spectral roll-off; higher noise ratings, especially in higher frequencies (2.5 kHz and above); an open quotient (OQ) close to one, indicating that full vocal fold closure rarely or never occurs during the cycle; a more sinusoidal pulse shape with a shallower closing phase; and a DC offset: measurable baseline airflow during the “closed” phase (see, e.g., Fant 1993, 1995; Hanson 1997; Holmberg et al. 1988; Karlsson 1988; Klatt & Klatt 1990; Monsen & Engebretson 1977; Price 1989; Södersten & Lindestad 1990). Greater frequency of breathiness among women is consistent with reports that a posterior glottal chink is typical for female speakers but less common in men (cf. section 1.3). It is important, however, to point out that considerable cross-speaker variation exists, and group comparisons usually show overlap between male and female subjects. For example, Holmberg et al. (1988) found that positive DC airflow was normal in both men and women during productions of repeated /pæ/. The 6 speakers analyzed in Löfqvist et al. (1995) did not show clear differences in open quotient as a function of gender; rather, 1 of the 3 females was distinguished from all other subjects by having a uniformly high OQ. Hanson (1997) found extensive variation in acoustic indices of breathiness among 22 female speakers. A complicating factor in this literature is that, as with f_0 , an individual speaker can produce a range of voice qualities, so that gender effects may reflect both structural differences and aspects of laryngeal settings chosen partly in response to culturally defined notions of appropriate or desirable voices (cf. Bickley & Stevens 1986; Klatt & Klatt 1990). Furthermore, many of the measures mentioned above vary systematically with pitch and intensity (Holmberg et al. 1988; Monsen & Engebretson 1977; Södersten & Lindestad 1990), so some interspeaker variation may be attributable to these prosodic factors.

The most heavily studied aspect of children's voices is undoubtedly fundamental frequency (f_0). Although it is clear that average f_0 decreases during childhood, defining the nature and time span of this decline has not been so simple. Early data from Eguchi and Hirsh (1969) showed a major drop from 3 to 6 years followed by a more gradual decline, whereas Titze (1989) surveyed previous literature and concluded that f_0 decreases slowly over ages 3 to 10 and then shows a major drop in boys. Most studies do not find significant gender effects in f_0 at young ages, but there is probably a slight trend toward lower average f_0 's in boys than girls (cf. Kent 1976), possibly the result of gender differences in intonational patterns and ranges (Ferrand & Bloom 1996; McAllister et al. 1994). Although some authors have attempted to use developmental changes in f_0 as a metric of laryngeal growth, the children's f_0 data may be confounded by the same socio-cultural factors mentioned above for adults and also by differences in speech materials across studies. For example, studies of younger children almost always analyze spontaneous speech, whereas older children may be asked to produce test items under more controlled circumstances where f_0 variation may be more limited.

Along somewhat similar lines, researchers have tried to trace growing neuromuscular stability in the larynx by following trends in f_0 variability or perturbation measures. Eguchi and Hirsh (1969) established the general result that intra-subject variability in f_0 declined over a period of 10 to 12 years. Ohde (1985) found higher SDs and CoVs of f_0 following stop releases in 8- to 9-year-olds than adults, but pointed out that these results could reflect variability in children's intonational contours as well as fine-grained laryngeal control. Glaze et al. (1988) found no differences in jitter (pitch perturbations) for children 5 to 11

as compared to adults, and reduced shimmer (amplitude perturbations) and signal-to-noise ratios (SNRs) in the children, the opposite of what one would expect if perturbation reflected neuromuscular development. McAllister et al. (1996) suggest that children do not show higher perturbation measures than adults as a general rule, but that this may obtain under running speech conditions where pitch and intensity undergo rapid change. They also point out that jitter, which is measured as a percentage of glottal period duration, may over-correct for f_0 differences between speakers, complicating interpretation of any age effects. Actually, results from Nittrouer et al. (1990) imply rather general problems with comparing jitter measures across groups. They observed a strong negative relationship between jitter and overall signal-to-noise levels in men, whereas in women jitter was not clearly related to overall SNR and showed only a possible weak relationship with high-frequency noise (band-limited SNR). Apparently, then, jitter measures may not reflect the same laryngeal variables in all subject groups.

Studies of other voice quality features in children are less numerous, but they tend to suggest that children's voices are more similar to women's than to men's. For example, Gobl (1988) measured aspects of glottal pulse shape in a single 10-year-old and 3 adult male subjects and found evidence of a breathier voice posture in the child. Bailey and Haggard (1980) comment that frequent breathy voicing in their 3- to 4-year-old subjects made definition of voicing onsets and offsets difficult. Some authors report a pattern of high open quotients in children (Sapienza & Stathopoulos 1994; Stathopoulos 1995); in other cases the salient effect is that children and women together have markedly higher values than men (Stathopoulos et al. 1990; Stathopoulos & Sapienza 1993b). Sapienza and Stathopoulos (1994) also found higher values of maximum flow declination rate

(i.e., faster closing phases) in men than in women or 4-year-olds (see also Stathopoulos & Sapienza 1993b; Stathopoulos 1995). This is despite Stathopoulos' suggestion that children may use higher speaking intensities than adults, since one effect of increased intensity may be a faster closing phase (cf. Gobl 1988; Sapienza & Stathopoulos 1994; Titze & Talkin 1979). Given the unique developmental pattern of pubescent boys, children's vocal folds are physically more similar to women's than to men's, so these age-by-sex interactions are not surprising. It may also be that children adopt slightly abducted voice postures as one means of compensating for higher laryngeal resistances; McAllister et al. (1994) noted that phonation threshold pressures were typically lower in women and children with posterior chinks.

1.5.2 Segmentally-related variation

Even in languages where voice quality is considered noncontrastive, predictable voice source changes may occur in the transitional regions between distinctively voiced and voiceless sounds (Fant 1993, 1995; Gobl 1988; Gobl & Ní Chasaide 1988; Klatt et al. 1968; Lindqvist 1972a; Rothenberg 1972; cf. also Hertegård et al. 1995). In particular, speakers pass through a period of breathy-type voicing as they move into and out of abducted states. The American speakers recorded in Löfqvist et al. (1995; see also Löfqvist & McGowan 1992) typically showed increasing airflows and open quotients for 50+msec preceding /h/, /s/, and /sp/ (in 1 female, open quotient was uniformly high and did not show much effect of consonantal context). Gobl & Ní Chasaide (1988) found increasing DC flow levels, decreasing AC flows, damping of F1, and added spectral noise beginning some 60 msec before stop closures in Swedish subjects. The French speakers in their study showed no such patterns, suggesting that these voice

quality changes result from learned aspects of interarticulator timing that may differ across languages. The British speakers fell into two groups, one Swedish-like in laryngeal behavior, and the other French-like.

Oral airflow reflects laryngeal behavior most accurately when minimal supra-glottal movement coincides with changes in glottal aperture. The consonant /h/ fits this description, and thus becomes an important source of data for us. The next section reviews the main phonetic characteristics of /h/ across languages.

1.6 The characteristics of /h/

A central hypothesis in this study is that voicing behavior for /h/ is relevant to understanding the voicing patterns in obstruent consonants. The open upper vocal tract necessarily implies that aerodynamic conditions during /h/ differ from those of more obstructed consonants in important ways. Voice source properties have been shown to vary with oral obstruction, generally with the effect of making pulse shapes more sinusoidal and amplitudes smaller (Bickley & Stevens 1986; Fant 1995; Gobl 1988; Rothenberg 1972). The intraoral pressure increase that accompanies stop closures, in absence of compensatory maneuvers, will tend to suppress voicing, and, indeed, this is one of the usual justifications offered for the generalization that languages are more likely to have voiceless stops than voiced (cf. Ohala 1983). So although the stop consonants are complex insofar as they require control of various articulators at once, in a purely aerodynamic sense it is easier to achieve voicelessness during a stop closure than during /h/ (cf. Lindqvist 1972a, 1972b; Rothenberg & Mahshie 1988). In fact, distinctive voicing contrasts in glottal fricatives appear to be fairly rare in natural languages

(Maddieson 1984), which could be taken to suggest that control of voicing is more difficult in /h/ than in stops.

Descriptive phoneticians have long recognized that /h/ in English may be produced with uninterrupted voicing, especially in intervocalic or unstressed positions. The main effect of stress is apparently to increase the degree of abduction, leading to greater differentiation between /h/ and surrounding vowels and giving /h/ more extreme features of breathiness such as sinusoidal pulse shapes, higher open quotients, weaker vocal tract excitations, higher spectral tilt, and increased DC airflow (Fant 1993; Gobl 1988; Pierrehumbert & Talkin 1992; Rothenberg & Mahshie 1988; note that Pierrehumbert & Talkin actually give a more finely grained analysis that differentiates between lexical stress and sentential stress, i.e., accent). Typically, AC amplitudes will also decrease steadily as the vocal folds become more abducted, reducing to 0 where there is a voicing break. Because voicing is noncontrastive in English /h/, a period of voicelessness *per se* is not mandatory; the production requirement appears to be simply some degree of abduction or, more generally, a change in glottal configuration that produces some of the characteristics of voicelessness. Acoustic measures on several speakers by Manuel and Stevens (1989) support the suggestion that /h/ production involves a period of increased breathiness relative to an individual's typical voice quality setting. Their measure was the H1-H2 amplitude difference (recall from section 1.5.1 that elevated H1 amplitude is one of the correlates of breathy voice quality). The absolute H1-H2 difference during vowels varied considerably across speakers, but nevertheless all speakers showed a relative increase in H1 amplitude during the interval identified acoustically as /h/.

Published data are inconsistent on the issue of how extensive abduction is for /h/ compared to other voiceless sounds. It is generally agreed that, other factors equal, speakers show larger abductions for (oral) fricatives than stops, and for aspirated than unaspirated stops (Klatt et al. 1968; Lindqvist 1972b; Lisker et al. 1969; Lisker et al. 1970; Sawashima 1968, 1979; Sawashima et al. 1970; Slis & Damsté 1967). But whereas some authors report extensive abduction for /h/ as well (Klatt et al. 1968; Slis & Damsté 1967), others find /h/ abductions to be quite modest, comparable to or less than those seen in aspirated stops (Lindqvist 1972b; Lisker & Baer 1984; Rothenberg 1972). Actually, when individual token data are presented, it appears that the abduction for /h/ may vary both within and across speakers (Klatt et al. 1968; Slis & Damsté 1967). The methods available for monitoring glottal aperture make quantifying this variability rather difficult, however: Fiberscopic data show effects of scope movement in the laryngopharynx (cf. Sawashima 1968), and electroglottographic data are a more direct reflection of tissue contact area than glottal area *per se* (Rothenberg 1979). Nevertheless, it is probably the case that the degree of /h/ voicing reflects, to some degree, variation in abduction extent.

Some of these considerations will be relevant for the interpretation of our results. They do not, however, invalidate the use of /h/ as a source of information on laryngeal and voicing behavior. In a sense, the fact that /h/ can be voiced or voiceless makes it uniquely useful for present purposes. Speakers presumably do not need to exercise the same degree of laryngeal control when voicing is noncontrastive as when it carries linguistic information, so that the voicing status of /h/ may follow straightforwardly from whatever conditions currently happen to exist in the glottis. Therefore, if there are population differences in factors relevant to voicing onsets and offsets, they should be most easily observable

here. Any such differences would imply that speakers arrive at functionally comparable speech outputs from varying initial conditions. The task of achieving those outputs, therefore, would likewise differ somewhat across groups.

Using /h/ to infer aspects of laryngeal function also avoids some of the problems associated with voice quality data. As noted above, voice quality may be affected by prosodic features such as intonational contour, and is also influenced by social factors and cultural norms. These considerations have made it difficult to interpret findings of gender differences in adults especially. In contrast, there is no known evidence that /h/ voicing carries significant pragmatic or affective information, so differences are more easily attributed to physical factors such as laryngeal structure or aerodynamic quantities.

1.7 General implications and aims of current study

The theoretical descriptions of vocal-fold vibration allow the possibility that individuals or groups differ in the extent to which various parameters are (or can be) manipulated to achieve voicing. The relative timing of laryngeal and supralaryngeal movements is clearly important for effecting the VOT differences that characterize stop voicing contrasts, and to some extent VOT development certainly reflects increasing skill in articulatory timing. At the same time, there are well-known developmental changes in many of the factors involved in voicing control, including glottal cross-sectional area, transglottal pressure, and vocal-fold tissue characteristics. These changes may well have implications for how children manage voicing onsets and offsets. Further, the same laryngeal factors that have been cited as explanations for adult gender differences in voice quality may also lead to passive or actively controlled differences in articulation

for voiceless consonants, even in the face of comparable timing-control abilities and similar respiratory support.

To gain greater insight into how voicing control may differ among normal speakers of varying age and sex, the study described below analyzes oral airflow and pressure data from men, women, and 5-year-old children producing voiced and voiceless stops as well as /h/. VOT measurements for the stops are obtained and compared among groups, extending our understanding of the developmental progression for voiceless aspirated stops. A measure of /h/ voicing, VOT_h, is defined in a manner somewhat analogous to traditional voice onset time. This reveals some interesting individual and group differences and provides one means of comparing the results for /h/ to those for the voiceless stops. In the manner of previous authors who have used airflow signals to infer laryngeal behavior (e.g., Gobl 1988; Klatt et al. 1968; Rothenberg 1972), the DC flow contours around /h/ are taken as a source of information on changes in glottal aperture. Combined with the pressure and voicing data, this allows inquiry into the conditions surrounding voicing onsets across speakers and speaker groups. Relationships among peak flows, voicing onsets, intraoral pressure, and body-size measures are analyzed for each group in an attempt to identify the speaker characteristics that most favor voicing during abduction (i.e., during /h/). Analysis of individual tokens of /h/ within speakers provides further information on the factors that influence voicing thresholds across normal populations.

2. Methods

2.1 Subjects

Subjects were recorded from three populations: Normal adult males, normal adult females, and normally developing 5-year-old children. Airflow data were gathered from 7 men, 7 women, 4 boys, and 3 girls. Valid intraoral pressure signals were obtained for 6 of the 7 subjects in each group,^{2,1} so results are reported below for either 18 or 21 subjects depending on whether the pressure data were essential for analysis or interpretation. Table 2.1 lists the ages and identification codes of all subjects.

Adults were considered eligible if they were native speakers of American English and reported no history of speech, language, or hearing disorders. An attempt was made to record subjects of varying ages and physical builds, without going to unusual extremes on either dimension. The range of ages for the men was 31 years, with a mean of 35.4 years. In the women the range was 24 years, with a mean of 37.5 years. Note that adult female AF7-LK is the author.

Child subjects were considered eligible if their first and dominant language was English and if their parents reported no history of diagnosed or suspected speech, language, or hearing disorders. The children ranged in age from 4.7-5.9 years (4;8-5;11), with a mean of 5.4 years (about 5;5). All had lived in the New Haven, Connecticut, area for at least three years at the time of testing and none had experienced extensive or protracted exposure to other languages (see Table 2.2 for additional details). Parents were asked informally

about the child's development at the time of initial contact and a more detailed questionnaire was filled out at the time of recording. Some parents reported previous treatment for ear and/or throat infections (cf. Table 2.2). In such cases, the parent was questioned further to ascertain that 1) at the time of recording, the child was healthy and had been symptom-free for at least one month, and 2) any previous episodes of otitis media had not been of sufficient duration and/or severity that the child would likely have experienced long periods (4+ weeks) of reduced auditory input.

To verify that language skills were age-appropriate, a short speech sample was collected for each child immediately before the aerodynamic recordings were made. In most cases, the child told a story either of his/her choosing or based on an illustrated book; in one case (5F2-EC), the sample consisted of a conversational exchange. The sessions were recorded onto cassette tape using an Onkyo TA-RW11 tape recorder and a Realistic unidirectional dynamic microphone (33-1073A) in an acoustically shielded room. These samples were subsequently transcribed and coded according to the conventions documented for Miller and Chapman's (1993) Systematic Analysis of Language Transcripts (SALT) programs. Results confirmed that all children showed a mean length of utterance (MLU) within or above the expected ranges for their age, based on the extrapolated linear fit obtained for Miller and Chapman's (1981) normative sample of 123 middle-class Midwestern children aged 0–60 months. Summaries of the SALT analyses are given in Tables 2.3a-b.

In keeping with standard procedures of informed consent, adult subjects and parents of child subjects received a written description of the experimental

methods and purpose and gave signed consent to their participation before any recording began. Copies of the consent forms are given in Appendix B. We gave the children a verbal explanation of the procedures and equipment at the beginning of the recording session.

2.2 Speech materials and elicitation

Speech materials were the same for child and adult subjects: Utterances of the form *mama CАpa*, in which the third syllable received primary stress and had as its initial consonant one of the set /b, d, p, t, h/; e.g.: [,mamə 'pʰɑpə].

Thus, target consonants always occurred within a connected speech context and began a stressed syllable. The form of the frame was chosen to make no more than modest articulatory or memory demands on subjects and to allow for easy and reliable measurement of a variety of articulatory and aerodynamic events.

Each subject was recorded in several input runs of up to 60 seconds in duration. During each run, subjects produced multiple repetitions of a single utterance, at a self-selected (comfortable) rate and with as many utterances to a breath group as they wished. The actual number of input runs and the order of utterances across the session varied across subjects. Adults usually produced 10–15 repetitions per input, with about 2–4 inputs per voiceless consonant, while child subjects usually produced 4–8 repetitions per input, and 4 or more inputs per consonant. Since no detailed analysis was planned for the voiced consonants, fewer tokens of /b, d/ were collected so that we could concentrate on /p, t, h/ during recording sessions. The number of tokens we could reasonably gather from our child subjects was 20–30 per

voiceless consonant. More tokens were collected from adults to increase the likelihood that any subtle gender differences might be detected. Tables 3.1, 3.2, 3.3, 3.5, 3.6 (giving distributional statistics for VOTs, vowel durations, /h/ flow peaks, /p/ pressure peaks, and VOT_h, all discussed in chapter 3), include the number of tokens measured for each subject.

Utterances were presented to subjects orally, beginning with *mama PApa*, the one most easily interpreted as an actual English utterance. Subjects repeated this several times while signal input levels were set, and the first input run(s) continued with this utterance. After several tokens of an utterance type had been collected, the next was introduced, and multiple repetitions were collected. (The children were allowed to pause between every utterance type to place a colorful sticker on a game page, charting their progress through the experiment. This provided them with an additional 2- to 3-minute delay between utterance types.) Most utterances, especially those containing the voiceless consonants, were revisited one or more times during the recording session until we had a reasonable number of tokens for each consonant. When introducing a new utterance type, reference was sometimes made to a similar-sounding word (e.g., “mama HApa, like hopping down the street”). In general, one or two repetitions by the experimenter was enough for subjects to reproduce the utterance correctly, and no subject objected to any of these novel utterances or showed any signs of difficulty with the task.

Sawashima et al. (1983) reported correlations between actual vocal-fold length (measured by calibrated filming techniques) and various additional measures in adults. They found that vocal-fold length correlated best with minimum modal fundamental frequency in men, and with neck circumference in

women. Therefore, after all experimental utterances had been collected, a final recording, acoustics only, was collected from subjects producing their minimum modal fundamental frequencies on a sustained /a/. Subjects were asked not to “tuck their chins down” and not to let their voices “crack or break,” with the experimenter demonstrating creak phonation at a low f_0 . Most subjects found it easiest to begin on a fairly low pitch, then descend as far as possible. If a subject did start to produce aperiodic phonation, s/he was asked to raise the pitch slightly until modal phonation resumed.

Finally, two measures of physical size were made: neck circumference at the level of the protrusion of the thyroid cartilage, and standing height (without shoes). The neck circumference measure was taken as a gross indicator of larynx size (again following Sawashima et al. 1983). Measures of height have been found to correlate well with lung volumes in children as well as adults (Hepper et al. 1965, Polgar & Weng 1979). The body size and minimum f_0 measures are discussed in connection with subject voicing patterns in Section 3.4.

2.3 Recording procedures and equipment

Figure 2.1 diagrams the experimental setup used during recording sessions. Acoustic and airflow signals were collected for every utterance. Acoustic signals were filtered at 9.5 kHz and digitized at 20 kHz, while pressure and airflow signals were filtered at 4.5 kHz and digitized at 10 kHz, all with 12-bit precision. The acoustic signal was obtained using a standing microphone positioned near the subject. Since the microphone was outside the mask used

for collecting airflow signals, it received a somewhat damped speech signal. The acoustic signal was used mainly for verifying syllable identities.

Airflow was recorded using 1 of 3 differently sized, sterilized Rothenberg masks (Glottal Enterprises models MA-1N, MA-1S, and MA-1P). These are modified plastic respiratory masks with screen vents and two small orifices for introducing differential pressure transducers (typically, one for pressure, one for flow). The system has a flat frequency response from DC to about 1000 kHz (cf. Badin et al. 1990). Adults held the mask to their faces themselves during recordings; for child subjects, a second experimenter either held the mask or else monitored the child and/or assisting parent to make sure that a good seal was maintained. The masks used here cover both the nose and the mouth, so the output signal represents oral and nasal flow combined. For oral sounds, nasal airflow was assumed to be negligible. In fact, a few subjects produced some obviously nasalized vowels in the *mama* portion of the carrier phrase, and as a result durational measurements could not be made on many of these syllables. No similar difficulties were encountered on the vowels in the target syllables, however, flanked as they were by oral consonants in all cases.

Intraoral air pressure, also digitized at 10 kHz, was recorded for a subset of utterances containing /h, p, b/ via an open-ended plastic tube introduced through one of the orifices in the mask to rest between the subject's lips during bilabial closure at a roughly horizontal angle. A catheter-tip pressure transducer (Millar SPC 350) was fed into the tube and positioned with its tip just inside the mask. These utterances were collected as a block either at the beginning or the end of the recording session. For the adults, an informal

attempt was made to balance the input order across subjects. For the 5-year-olds, the order depended mostly on the child's demeanor: More hesitant subjects were introduced first only to the mask, and the tube was added later.

Immediately following each recording session, flow calibration signals were obtained using a rotameter, sampling at several 5 l/m steps over the range 0–35 l/m. Pressure calibration signals were collected using either a U-tube or (more typically) a standing water manometer. Here, a range of values from 1–12 cm H₂O was sampled, in 1 or 2 cm steps. Separate pilot testing indicated that these two methods yielded virtually indistinguishable calibration values.

2.4 Signal processing

Signals were stored on a VAX computer and analyzed using the Hades signal analysis program at Haskins Laboratories (cf. Rubin 1995; Rubin et al. 1991; Rubin & Löfqvist 1996). After dethreading the input signals into their three components (acoustics, flow, and pressure), calibration equations for flow and pressure were derived from the recorded calibration signals by taking a signal average over a few hundred milliseconds during the times when the rotameter or manometer values were being announced. The physical units and the average values from the signal were then entered into a simple linear regression to obtain a calibration slope between signal values and physical units. Calibration intercept values were determined separately for every input signal by taking a mean over a region that should approximate zero in a properly calibrated signal: In flow signals, the average was taken for a region in the /p/ closure following the stressed syllable (recall that the fourth, final syllable of every utterance was *pa*), while in pressure signals, it was taken

during the vowel of the stressed syllable. These values were then entered into the slope equation to determine a unique intercept for each signal. This procedure provided some correction for baseline drift across utterances, and allowed the possibility of changing offset levels (holding gain constant) during a recording session if signals began to show clipping.

Signals were then smoothed as follows: Each flow signal was smoothed twice consecutively with a narrow triangular window (5 points, or .5 msec) to eliminate noise and allow easier identification of glottal pulses. All original flow and pressure signals were also smoothed once with a wide triangular window (133 points) to obliterate all or most evidence of glottal pulses. In a few adult males, residual pulsing remained after this step, and could only be removed by means of multiple smoothing operations. Since repeated smoothing would have the concurrent effect of flattening out the DC flow variations (which were of interest), the AC variation was left in these signals and constitutes a minor added source of variability in the flow peak measures for these subjects. From the smoothed signals, the first time derivative of the flow was derived and smoothed, also with a window size of 133 points. In a few subjects, the resulting signal showed considerable high-frequency, low-amplitude oscillation, making unique determination of zero-crossings difficult. In these cases, the original signal was smoothed one or two more times and then the first derivative taken again. Inspection of a few before-and-after cases verified that the additional smoothing eliminated the local oscillations but did not have much effect on major excursions. For utterances containing target stop consonants, the second time derivative was also obtained and smoothed.

For the utterance *mama HApa* only, each individual occurrence of the consonant was extracted from the flow signals by selecting a region around the flow peak representing /h/ abduction. Durations of 150 msec before the peak and 350 msec after it were chosen to include the full flow excursion for the /h/, as well as to show the closure (zero flow) during the following /p/. This served as a check on the accuracy of the calibration values for the complete signal, and insured that variability in the /h/ peak reflected primarily differences in abduction and not signal drift.

2.5 Measurement procedures and criteria

A number of measurements were made interactively for each utterance by identifying landmarks in the aerodynamic signals or in their first or second time derivatives.

2.5.1 Stop VOTs

Voice onset time for the stops was measured from the flow signals by locating two events (see Figure 2.2): 1) Oral release was defined as the local maximum in the second time derivative corresponding to substantial flow increase. In Figure 2.2, this is the point marked "PkRel3" (the 3 means that this was the third repetition in the input run). A concurrent release burst was often, but not always, visible in the acoustic signal.^{2.2} The few tokens showing multiple releases or incomplete closure were discarded. 2) Voicing onset after stop release was located visually in the flow signal (which typically showed low-amplitude pulsing more clearly than did the acoustic signal). To keep judgments consistent across consonants and speakers, a convention was adopted to place voicing onsets at the beginning of the first clearly definable

whole pulse that initiated periodic pulsing. The point of voicing onset in Figure 2.2 is marked "Vc3."

Two comments should be made in this context about measuring VOTs in /b/ and /d/. First, tokens of /b, d/ that showed continuous voicing during the closure were defined here as having 0 VOTs, since in running speech the onset of voicing for such stops cannot be measured as an independent event (cf. Lisker & Abramson 1967). This effectively collapsed measurements for /b, d/ into a single VOT distribution for contrast with the voiceless aspirates. (Recall that the reason for collecting voiced tokens at all was simply to ascertain that all subjects, particularly the children, demonstrated a clear difference in production between /b, d/ and /p, t/.) Second, the convention of locating voice onset at the beginning of a pulse had the effect of elevating VOT values slightly for voiceless unaspirated productions (i.e., the devoiced allophones of /b, d/) in tokens where the first glottal pulse coincided with the (larger) flow peak corresponding to the release burst. In such productions, the first *definable* pulse followed the flow peak corresponding to the burst (see Figure 2.3). The potential overestimation of VOT resulting from this definition would be most pronounced for speakers with the longest glottal periods, that is, the adult men with the lowest f_0 's.

2.5.2 Vowel durations

In utterances containing target /p/, three additional locations were marked in the flow signal and used to measure vowel duration, taken as a general indication of speech rate.^{2,3} In Figure 2.2, these are the points labelled "M1Rel3," "M2Clos3" and "Val3." 1) The release of the first /m/ in /mama/ was marked at the point where the flow signal showed an increase in

amplitude and/or in high-frequency pulse components. The acoustic changes accompanying this transition were typically quite robust even through the mask, and appearance of higher-frequency components in the spectrographic display was often a useful additional indication of /m/ release, especially when the subsequent vowel was somewhat nasalized. 2) Analogous cues were used to define the closure for the medial /m/ in /mama/. The duration from initial /m/ release to medial /m/ closure defined "Vdur1," the unstressed vowel duration. (Strictly speaking, this syllable usually received some secondary stress, that is, the utterance took a trochaic form with primary stress on the third syllable.) 3) The local minimum in the second time derivative corresponding to substantial flow decrease defined oral closure for the unstressed /p/ of the carrier phrase. The duration from target /p/ release to the /p/ closure of the fourth syllable defined "Vdur2," the stressed vowel duration. For some of the child subjects, vowel duration measures could not be made, either because the subject tended to devoice the end of the stressed syllable or because there was not a consistent release from the /m/ into a vowel in the first syllable.

2.5.3 Intraoral pressure peaks

Pressure peaks during the unstressed /p/ of the target utterance were defined according to major zero crossings in the first time derivative of the smoothed pressure signal. An example is shown at the bottom of Figure 2.4, with the zero-crossing indicated as "Z." The peak pressure values thus obtained were taken to approximate the subject's subglottal pressure level for the utterance. Below, these intraoral pressure peak values are variously referred to as intraoral pressure, subglottal pressure, or simply pressure, depending on context.

2.5.4 Voicing of /h/

To determine how characteristics of voicing onsets were related to the abduction maneuver, the time of voice onset relative to /h/ peak was determined. This duration is referred to as the VOT_h since it bears some similarity to the voice onset time measure used for stop consonants. (It is not totally analogous in that VOT is defined as the time interval between stop release and voicing—i.e., a laryngeal event relative to an oral one—whereas VOT_h is the time between flow peak and voicing onset, that is, two laryngeal events. VOT_h and VOT for an aspirated stop are similar insofar as they are both durational measures of voiceless intervals associated with specific consonants.) The /h/ flow peaks were determined from the major zero crossings in first time derivative of the smoothed flow signal (label “Z” in the middle panels of Figure 2.4). The peak airflow, measured in l/m, was taken as an index of the degree of glottal abduction for /h/ and provided a value for calculating laryngeal resistance (=pressure/flow) at the point of maximum abduction (cf. Holmberg et al. 1988; McHenry et al. 1996; Miller & Daniloff 1993; Netsell et al. 1994; Rothenberg 1973).

In cases where clear voicing continued unbroken through the /h/ flow excursion, voicing onset was defined to be coincident with the flow peak so as to yield a VOT_h of 0 (see left side of Figure 2.5). A cessation of voicing around the flow peak, on the other hand, was measured as a positive VOT_h (right side of Figure 2.5). But whereas voicing onsets after stop releases could be determined with ease by simple visual inspection of the flow signal, the /h/ presented unique problems that called for a different method of determining voicing offsets and onsets. In some subjects, for example, /h/ tokens

contained short regions of flow undulation which seemed periodic visually but which did not present amplitude or frequency characteristics consistent with those of the weak voicing one could observe clearly after some voiceless stops in these same subjects. In other cases, the /h/ flow excursions were accompanied by short-term aperiodic disturbance (i.e., noise) of sufficient amplitude that weak pulsing might be masked.

To cope with these problems and make measurements of /h/ voicing with confidence, a technique based on the spectral composition of the signal was adopted. The method is outlined in Figure 2.6. Briefly, a narrow-band Discrete Fourier Transform was applied to the flow signal (DFT - window size=512, window skip=64, Hamming window) and used to create a waterfall display of the region around the flow peak. Analysis was performed over a region that included several clear glottal pulses in the vowels preceding and following the /h/, to allow definition of the main spectral characteristics of vocalic regions. This definition was made separately for each subject but typically included the presence of strong first and second harmonics, sometimes with evidence of higher harmonics as well. The DFT parameters yielded spectral slices (frames) of 6.4 msec and imposed temporal quantization on the signal such that stepping through a token frame-by-frame usually revealed rather abrupt spectral changes as voicing ceased or started. The frame when abrupt changes were observed was recorded, and the midpoint of this frame was taken as the location of voicing offset or onset. Trial comparisons with a few clear tokens for several subjects showed good agreement between the times chosen in this manner and those chosen by simple visual inspection of the flow signal.

Once the flow peak and voicing onset had been defined, measurement of time and flow variables was carried out for all tokens of /h/. To obtain more information about the characteristics of voicing behavior around abduction maneuvers, several pulse-by-pulse measures were also made on the /h/ tokens, as shown in Figure 2.7. Automatic peak-picking was used to mark individual glottal pulses, beginning with voicing onset for /h/ and continuing through the entire stressed vowel (i.e., until the closure for the following /p/). Period durations were calculated and converted to fundamental frequency, and pulse amplitudes were obtained as the difference between the smoothed and unsmoothed flow signals at the time of each pulse peak. In effect, this subtracted off the baseline (DC) flow to give a measure of the alternating (AC) flow. Whereas major variation in the DC flow reflects valving actions at the larynx or in the upper vocal tract, the AC flow reflects the glottal area change during each cycle and provides an index of the vibratory amplitude of the vocal folds. These f_0 and AC flow measures were used in the token-by-token analysis of voicing thresholds (sections 3.4–3.5). Average f_0 and AC flow traces were derived for each subject as well. Tokens were aligned from the onset of voicing and averaging across tokens was done a pulse at a time until the number of tokens included in the average began to fall well below the total number of recorded tokens. Defining this cutoff served essentially to cut the ends off tokens with very vowel durations, that is, many pulses. These averaged traces were used in interpreting the /h/ voicing data. They also provided average f_0 's for each subject at the vowel onset (the mean of the first two pulses) and midpoint (the value of middle pulse). These two values were taken as an indication of changes in laryngeal tension as the subject moved from abducted conditions into the stressed vowel.

A third and final f_0 measure was taken from the minimum modal f_0 recordings (acoustics only; cf. discussion above under section 2.2). A region of a few hundred milliseconds was selected that was perceptually low-pitched (most subjects varied their pitch some as they tried to find their minimum) and which did not evidence notable aperiodicity or breathiness, either auditorily or visually, in the acoustic display. Within this region, narrow-band spectra (DFT window size = 512, window separation = 128, Hamming window) were obtained for 3 time frames where a number of higher harmonics could be easily defined. In each of these frames, the frequency of a strong higher harmonic was taken and divided by the harmonic number to yield a value for f_0 . The values from the 3 time frames were then averaged to obtain a single minimum f_0 value for each subject. For one child (5M2-SS), the audio signal was lost for the minimum modal f_0 input, so his minimum f_0 was estimated by obtaining and averaging values from unstressed syllables preceding /b/ and /d/. Although the resultant value may have been somewhat higher than the subject's true minimum, it was at least a measure of his f_0 in absence of stress and abduction effects.

When all of these locations had been defined in the signals, automatic procedures within the HADES program were used to obtain numerical values of time and amplitude at each location. All amplitude measures of both pressure and flow were made in the smoothed signals. The raw data were subjected to distributional analysis using the BMDP software package (cf. Dixon 1992). VOT and VOT_h measurements were rounded to the nearest 5 msec; pressure values were rounded to the nearest .5 cm H₂O; flow amplitudes on /h/ were rounded to the nearest 5 l/m. Preliminary analyses

were checked for unusual values, and analyses were re-run for any mis-labeled files. These values were then transferred to StatView (Macintosh version 4.5) for tabulation, plotting, and statistical treatment (analysis of variance and linear regression).

2.5.5 Measurement reliability

To provide an index of measurement reliability, 5% of all tokens were re-measured, using identical procedures, several months after the original analyses were done. The two data sets were subjected to correlational analysis and mean differences for measurements were calculated. Results are summarized in Table 2.4. There was near-perfect agreement for the pressure ($r > .9995$, $p < .0001$) and flow peak ($r = .999$, $p < .0001$) values, both obtained at zero crossings of the first derivative. For the durational measures (VOT for the 4 stops, VOT_h, and vowel duration), average differences were less than 2 msec, with $r \geq .96$ and $p < .0001$ in all cases.

Notes

2.1 The seventh subject in each group represented a partially successful run. AM1-RM was the first experimental subject, and was recorded using Glottal Enterprises transducers for both flow and intraoral pressure. The resulting pressure signal included some /p/'s that nearly or utterly lacked a pressure increase and also showed an unusual range (4–20 cm H₂O) of peak values in the absence of loudness or other noticeable differences in flow or acoustics. These poor results led us to switch to the catheter-tip transducer for all other recordings.

My own pressure signals were discarded because several of them showed significant baseline drift. This probably reflected the sensitivity of the catheter-tip transducer to temperature variations, including those induced by

body heat. Collecting data on myself involved intermittent handling of the equipment as I moved between the recording devices and the computer terminal where the inputs were cued.

The signals for 5M3-LEZ showed that our catheter-tip transducer needed replacement. Subsequent subjects (5M4-MM and AM7-BG) were run with a similar but upgraded transducer.

One subject, AF5-MD, was recorded on two separate occasions. In her first data-collection session, the pressure signal showed minor but widespread peak clipping. Her second session concentrated on utterances with /h/ and bilabials (those for which a pressure signal could be recorded). Combining the data from the two recording sessions turned out to be impractical because of slight differences in pressure and airflow levels. Thus, data reported here come from the second session only, *except* for utterances containing /d/, for which no tokens had been collected in the second session.

2.2 In preliminary analyses, stop releases and closures were marked at the points where the unsmoothed flow signal suddenly rose from or dropped to a baseline value. This criterion proved difficult to follow in certain cases where the flow signals showed a somewhat concave shape at stop release. This was seen most often for the stressed /p/. Using the second derivative allowed a precise definition of release in terms of the maximum peak corresponding to major flow increase after the release.

Peter Ladefoged (personal communication) has expressed some concern about these cases of nonabrupt flow increases at a stop release, since one would usually expect a plosive release to be accompanied by a very sudden rise in airflow corresponding to the discharge of intraoral pressure. However, in previous work with this system (Löfqvist et al. 1995; see also McGowan et al. 1995) we have observed that the oral flow signal may show subtle effects of articulatory movement (that is, in addition to the extreme changes brought on by forming and releasing major constrictions in the vocal tract). My interpretation of these nonabrupt flow increases is that the movement out of the /p/ into /ɑ/ involved some jaw retraction, increasing the volume

between the subject's face and the airflow mask and modulating the flow increase brought on by simply opening the lips.

2.3 These duration measures were chosen for practical reasons having to do with specific characteristics of this data set. The rhythmic structure of the utterance was such that the second and fourth (final) syllables in the utterance were often quite weakened, making it difficult to define boundaries in the signals. For example, it was not uncommon in some speakers to find the second, unstressed *ma* rendered as a syllabic nasal, with no clear vocalic region between the /m/ and the following /p/ closure. In the final syllable, the vowel was frequently devoiced or produced with low-amplitude and sometimes aperiodic pulsing. Any of these features complicate a definition of vowel margins. Vowel duration was chosen over syllable duration primarily because the /m/ in the first syllable showed extensive variability for some speakers (with no clear group patterning), and evidently served as a "verbal pause" between successive utterances. In these cases, measures of syllable duration would have shown substantially increased variability without (it would seem) providing any more useful information.

3. Results

3.0 Overview

The voiceless stops serve as a starting point for a more general inquiry into voicing behavior. Thus, section 3.1 presents VOT data from our 3 speaker groups, in the traditional form of histograms for contrastive homoorganic pairs. The consonant /h/ provides a means of investigating voicing behavior without the complications of upper articulator activity. General characteristics of the /h/ data are considered first (section 3.2), and then /h/ voicing (VOT_h) results are presented and compared to the stop VOT data (section 3.3). This comparison suggests that /h/ production can reveal some interesting and relevant features of voicing behavior across speakers. Sections 3.4 and 3.5 present more detailed analyses of phonatory behavior around /h/ in an attempt to define the factors most important for determining voicing and devoicing in men, women, and children.

3.1 Measures of VOT in the stop consonants

Figures 3.1 and 3.2 show VOT histograms for /b, p/, and /d, t/, respectively. Figures 3.3 and 3.4 replot /p/ and /t/ only, using an expanded vertical scale to show the distributional shapes more clearly. Descriptive statistics are given in Tables 3.1–3.3 for the stop VOT and vowel duration measures. Table 3.4 provides an overview of the data, showing group averages for means, medians, and standard deviations of VOT and vowel duration measures. Medians as well as means are included since a number of measures, especially those for /p, t/ VOTs, were significantly skewed such that mean values were not representative

of the bulk of productions (cf. discussion in section 1.1). The non-normality of the VOT data is also evident in the *W* statistics and associated *p*-values shown in Tables 3.1–3. Values for *W* range from 0 to 1, approaching 1 as the sample becomes more normal (Dixon 1992). Significant values of *W* are typical in these data, another indication that simple means and standard deviations are not adequate representations of the data.

Predictably, all adult subjects showed distinct VOT distributions for each voiced-voiceless pair, usually with slight overlap. The overlap is not surprising given that these consonants were produced in a connected speech context (cf. Lisker & Abramson 1967). Recall also that the measurement criteria used here may have tended to overestimate VOT lags in /b/ and /d/ (cf. section 2.5), possibly contributing to overlap. The children's histograms also show roughly distinct distributions in /b, p/, and /d, t/ pairs, albeit with somewhat more overlap and less separation between the two categories. Mann-Whitney U-tests indicated highly significant differences as a function of voicing category for all children and adults (in most cases $p \leq .001$; see results in Appendix C), in keeping with our expectation that the voicing contrast should be well-established in normal 5-year-olds.

To explore group effects in VOT and vowel duration measures, analyses of variance (ANOVAs) were performed on subject means, medians, and standard deviations. Full results of these tests are given in Appendix D. No significant group differences were found for means or medians of VOT in any of the stops. Figure 3.5 plots the median values for /p, t/ VOTs and vowel durations for all subjects. This shows that individual children spanned the full range of adult values; that is, there was no trend among the 5-year-olds toward either longer or

shorter values compared to adults. The only hint of a group difference in Figure 3.5 may be a slight tendency toward longer VOTs in women than in men. Table 3.4 confirms that the men produced shorter /p, t/ VOTs than either the women or 5-year-olds. For stressed vowel durations, group effects were nonsignificant, but for the unstressed vowel in *mama*, longer durations were found in the children than in the adults (for means, overall $F_{2,15}=7.067$, $p=.007$). Equivalent durations for the men and women may be taken as evidence that speech rates were comparable across gender in adults. The significant result for unstressed vowel duration is more difficult to interpret, since only a subset of the children provided data for the comparison. As mentioned in chapter 2, difficulties in defining acoustic boundaries for vocalic regions precluded measuring unstressed vowel durations for 3 of the 7 children.

Consistent with a number of previous studies (e.g., Eguchi & Hirsh 1969; Kent & Forner 1980; Ohde 1985), the child subjects here showed larger standard deviations than adults in the voiceless stops, but not the voiced. The children were also more variable on both measures of vowel duration. Figure 3.6 plots each subject's standard deviations for /p, t/ VOTs and vowel durations. The ANOVAs show strong group effects on all four measures, and post-hoc Scheffé tests indicate that the age difference holds in all paired comparisons (cf. Appendix D). In contrast to the medians (Figure 3.5), the standard deviations are uniformly higher in children than adults.

To correct for the possibility that greater standard deviations in children arose simply as a function of longer durations (see discussion in chapter 1), coefficients of variation ($CoV=SD/mean$) were calculated for the 4 variables shown in Figures 3.5 and 3.6. ANOVA results for the CoV were generally comparable to

those for standard deviation (cf. Appendix D), though significance levels were diminished for the unstressed vowel comparison (for the paired comparison between children and men reaching, $p=.06$). Thus, children's greater variability may arise partly out of durational differences, but cannot be attributed to them entirely. Another way of appreciating this fact is to compare Figures 3.5 and 3.6. Whereas in Figure 3.5 the children differentiate themselves from adults only on the unstressed vowel duration, in Figure 3.6 there are clear differences between adults and children in all 4 plots. Figure 3.6 also shows that individuals who vary extensively on one measure often do so on others as well. Across subjects, highly significant correlations (usually $p < .001$) are found for standard deviations of stressed vowel durations and /p, t/ VOTs (these data are given in Table 3.8, where they are discussed in greater detail). Significant relationships with the unstressed vowel, on the other hand, are less frequent and weaker overall. One should note that since the stressed vowel duration was defined as the time from stressed /p/ release to following /p/ closure, it incorporates the voice onset time for the first (stressed) /p/. This no doubt contributed to the strength of the relationship.

The correlations that speakers show between VOT values for different stops of the same voicing category are probably related in part to general speech characteristics such as speaking rate. Of greater interest here is the extent to which VOT in voiceless stops also reflects factors specifically related to laryngeal control. We approach this question through analysis of abduction and voicing for /h/.

3.2 Measures of /h/

3.2.1 General characteristics of abduction for /h/

Tables 3.5a–c present detailed statistics for flow amplitudes at the peak of /h/ abduction and peak intraoral pressure during the unstressed /p/ closure of the carrier phrase. Full ANOVA results for these measurements are included in Appendix D. Note that Tables 3.5 show all available pressure measurements for each subject, and therefore include data from utterances including target consonants /p, b, h/. A separate ANOVA indicated significant differences as a function of target consonant. The overall effect was that /b/-containing utterances tended to have slightly higher pressures than /p/- or /h/-containing utterances (mean differences < .5 cm H₂O), possibly as a result of greater pressure expenditure over the course of utterances containing the voiceless sounds /p/ and /h/. Although the group-by-consonant interaction was not significant, inspection of individual subject data showed that this pattern was most consistently true within the adult male group. The summed data in Tables 3.5 are presented as the closest approximation to the subjects' average pressure over all utterances and consonant types. In the extensive analyses of /h/ tokens below, only pressure measurements from /h/-containing utterances will be used.

In agreement with most previous reports, pressure values here did not differ significantly between men and women. Adult-child differences did not reach significance either but do show a trend toward higher pressures in children than adults. The average peak pressure for the 5-year-old group is 6.7 cm H₂O; for the women it is 6.3 cm H₂O; for the men, 6.1 cm H₂O. These pressure values are

consistent with those reported elsewhere for subjects using modest speaking intensities.

Previous studies also lead us to expect an increase in oral flow rate with age, and higher flows in adult men than women (cf. discussion in section 1.4), especially for voiceless consonants. The peak flow values for /h/ are roughly in accord with these expectations. ANOVA results show an overall group effect (for means, $F_{2,18}=3.88$, $p=.04$), with the post-hoc comparison showing higher flows in men than in children (also $p=.04$). The adult female group shows the widest range of flow peak values, overlapping both the men and the children.

Figures 3.7 and 3.8 plot the multiple smoothed tokens of /h/ for each subject. In Figures 3.7, all subjects are plotted on the same scale; in Figures 3.8 the vertical scales were chosen for each subject individually to reveal the patterns more clearly in subjects with lower flow rates. Tokens were aligned at the point of maximum flow, which is at 150 msec in these plots. (The peak flow values in Tables 3.5 were taken at these same time points.) As noted in chapter 2, the smoothing operations performed on these signals left residual pulsing for some of the adult male subjects. These oscillations constitute a minor added source of variability in the flow amplitude measures for these subjects.

All adult males show evidence of substantial laryngeal opening for /h/, with flow increases of 20 l/m or more. This characterization holds for some of the women and 5-year-olds, but not all. Subjects AF1-DR, AF2-MS, AF5-MD, and AF7-LK have flow increases comparable to those observed in the men, while AF3-PC, AF4-DB, and AF6-MP show more limited increases. The children's maximum flow peaks are nowhere near the adult maxima, but they are well

within the adult range as a whole. Neither age nor gender serves well to predict which children show the highest peak flows or ranges: The token plot for 5M2-SS, age 5;8, is comparable to that of 5F3-HH, age 4;8, while the plots for AM1-DJ and AF1-HJ, both 5;3, are roughly similar to each other and quite unlike those of either SS or HH.

As discussed in chapter 1, there are numerous reports of higher average token-to-token variabilities in temporal and postural measures among children than adults. Figures 3.7 and Tables 3.5 suggest that the extent of laryngeal abduction varies considerably, regardless of gender, in adults as well as children. Absolute ranges do not differentiate adults from children, nor do standard deviations. Although no attempt was made to measure the duration of /h/ flow excursions directly, perusal of Figures 3.7 does not suggest notable group differences on this dimension either, despite the significant differences in vowel duration noted above. What is distinctive in some of the children (specifically, 5M2-SS, 5F3-HH, 5M3-LEZ, and 5M4-MM) is a wide range of peak values extending up from the bottom of their flow range. Put another way, the adults that show the greatest variability are the same ones whose flow peaks are highest, whereas children may show comparable variability for lower absolute measurements. Thus, although the standard deviations of flow peak measures do not show group effects ($F_{2,18}=.173$, $p=.843$), the coefficients of variation do ($F_{2,18}=4.656$, $p=.023$; post-hoc testing shows $p=.02$ for men vs. 5-year-olds).

In contrast, the pressure values show group differences for both the standard deviation and the coefficient of variation. For standard deviations, $F_{2,15}=5.394$, $p=.017$; in post-hoc testing the comparison between men and children has a p -value of .03, and that between women and children shows $p=.07$. For coefficients

of variation, $F_{2,15}=4.299$, $p=.033$; post-hoc testing shows $p=.04$ for children vs. women and $p=.12$ for children vs. men. Performing the analysis on data from the /h/-containing utterances only yields similar results.

In an open vocal tract, oral airflow and subglottal air pressure are directly related via the laryngeal resistance (flow \times resistance = pressure). One question, therefore, is whether cross-subject variation in flow peak levels reflects major differences in speaking pressure levels. Figure 3.9 shows each subject's median flow values plotted against median pressure. Correlational analysis of these data yields utterly nonsignificant results ($r=.079$, $p=.77$), and no patterns are evident within any of the speaker groups either. Again, comparable results obtain if one correlates flow peaks with pressure values taken from /h/-containing utterances only. At this level of description, then, pressure and flow levels are essentially independent. This does not mean that flow and pressure are unrelated within single speakers; correlational analysis of multiple productions within speakers (discussed below) does yield significant results for some subjects. What it does mean is that subglottal pressure variation across speakers, whether owing to age-related factors or to differences in intensity levels, does not play a systematic role in determining the gross differences in /h/ flow peaks seen in Figures 3.7. The other major factor contributing to /h/ flow peak levels is, of course, the extent of glottal aperture. The /h/ flow peak results suggest that the child speakers were relatively more variable than adults in their abduction extents for /h/.

Variability in abduction rates is also evident in the expanded-scale plots in Figures 3.8. For most of the adult speakers, one observes a clustering of tokens whereby flow excursions show consistency over both amplitude and time. (An exception is subject AF6-MP, discussed below in detail.) In other words, the

adult subjects generally seem to have characteristic /h/ abduction gestures that show variation of scale, but retain a roughly common shape over repetition. Consequently, movements that reach greater extents are also longer. Such consistency can be seen in some of the child subjects (e.g., 5M1-DJ, maybe also 5M3-LEZ), but for most of the children it would be comparatively difficult to define a “typical” abduction pattern. Rates of flow increase and decrease may vary appreciably, so that tokens with high amplitude peaks are not necessarily those with the longest durations. In subjects with occasional flat or very low /h/ peaks, the presence of an abduction gesture itself appears to vary. In contrast, the three women who showed low-amplitude /h/ peaks (AF3-PC, AF4-DB, and, especially, AF6-MP) did so quite consistently. Finally, the children’s token plots show several occurrences of multiple flow peaks or extended plateaus. Two-stage laryngeal movements have been observed in adults under direct laryngoscopy (Cooke et al. 1997), and are occasionally evident in our flow signals as well, but complex contours are seen most frequently in the 5-year-olds. Thus, it is not just the case that children are more variable than adults in the relative degree of glottal opening they achieve. They are also more variable in how they get to their maximum abductions and in how they return to adducted postures.

The virtual absence of any flow increase for AF6-MP is unique among adults, and calls for further comment. Since her data were not rejected during preliminary auditory review, we must infer that a perceptually acceptable /h/ can be accomplished via laryngeal adjustments other than abduction *per se*. Defining a flow “peak” for centering MP’s /h/ tokens was in fact a difficult, sometimes dubious enterprise requiring magnification of the signals and relying partly on changes in pulse shape to determine an /h/ region. These pulse shape changes, toward a more sinusoidal form, suggested that the larynx was moving

into a breathy voicing posture in these regions. To investigate this possibility further, spectral sections were taken at single time frames in the middle of these regions of simple pulse shapes (that is, in the middle of “the /h/”) and well into the preceding and following vowels. Figure 3.10 compares spectra taken in the /h/ region (the darker traces) with those taken in the following vowel (the lighter traces) for a number of tokens. (A similar picture results if one compares the /h/ region with the preceding vowel.) Figure 3.10 shows reduced amplitudes for frequencies above c. 400 Hz in the traces representing the /h/. (The airflow mask used here is intended primarily to provide information on frequencies below about 1kHz, so the marked attenuation of frequencies above that cannot be taken as informative on voice quality.) A sinusoidal pulse shape and faster rate of spectral drop-off are both attributes of a breathy voice quality, and are presumably the features that rendered MP’s productions acceptable versions of intervocalic /h/. Although MP’s unusual pattern can thus be given a sensible interpretation, the lack of any measurable abduction movement will make her data irrelevant to much of the following inquiry into how voicing patterns vary during glottal abduction.

3.2.2 Voicing of /h/

Figure 3.11 shows VOTH distributions for all speakers. Recall that a VOTH of 0 msec indicates voicing throughout the /h/ abduction whereas higher values indicate the duration of the voicing break following the flow peak. Tables 3.6 give basic distributional statistics for VOTH, calculated first for all data and then only for tokens with voicing breaks (i.e., without cases of VOTH=0). It is readily apparent that extreme values of skew and significant W-statistics are typical here, making means and standard deviations inappropriate summaries of the data.

Consequently, questions about inter-subject differences in /h/ voicing were explored using the percentage of fully voiced /h/ productions and the total range of VOTH values. These measures are shown in Table 3.7 and Figure 3.12, respectively, and corresponding ANOVA results are included in Appendix D.

On the whole, the VOTH results confirm the traditional wisdom that full voicing of intervocalic /h/ is common among speakers of American English, even when the /h/ initiates a stressed syllable. At the same time, they suggest that a full discussion of /h/ voicing must make some reference to interspeaker differences. Moreover, these differences are apparently related to age and gender. As in our previous work (Löfqvist et al. 1995), the adult males usually produced /h/ with unbroken voicing. Subjects AM2-JG, AM5-LR, and AM7-BG produced no tokens with voicing breaks; the rest showed predominantly voiced /h/ with a scattering of devoiced tokens. In the two men whose /h/'s were most frequently devoiced (AM1-RM and AM6-ED), full voicing is still observed in 60–65% of the productions. The women showed a wider variety of individual patterns. Some, such as AF3-PC and AF6-MP, produced almost exclusively voiced /h/ while others, such as AF2-MS and AF7-LK, had few or no fully voiced tokens. The rest produced a mixture of voiced and voiceless tokens.

All 7 children produced a number of fully voiced /h/'s as well as some devoiced tokens. Within the child group, no simple age or gender effects are apparent: The girls (5F1–3: HJ, EC, HH) do not differ strikingly from the boys, and while on one hand the two subjects with the most widely scattered distributions, 5M1-DJ and 5F3-HH, were among the youngest, at the same time the ranges are almost as large for 5M2-SS and 5M3-LEZ, two of the oldest. Figure 3.12 shows that the children have wider overall ranges of VOTH than the adults ($F_{2,18}=6.464$, $p=.008$;

post-hoc tests show $p=.01$ for men vs. children and $p=.07$ for women vs. children). When cases of $VOT_h=0$ are removed, the group effects are less pronounced ($F_{2,18}=3.142$, $p=.08$ and in post-hoc tests the child-woman comparison does not approach significance). These differences in VOT_h range demonstrate that control of voicing varies considerably among 5-year-olds even when upper articulator movement is utterly lacking, and indicate that some of the variability in children's voicing measures is related to control over laryngeal and aerodynamic factors such as vocal fold tension, abduction degree, pressure, and flow.

The group differences in the percentage of voiced /h/ cannot be reduced to simple age effects. An ANOVA on this variable reveals a significant group effect ($F_{2,18}=5.255$, $p=.016$) reflecting a lower incidence of voiced /h/ in women than men. Neither of the child-adult comparisons reach significance. The heterogeneity of the adult female group is noteworthy, and recalls the wide spread of flow peak values seen in this group (cf. Figures 3.7 and Tables 3.5). It is not possible, however, to state global relationships between flow peak amplitudes and /h/ voicing across subject groups. For example, it is not the case that high percentages of voiced /h/ in children result simply from limited abductory extents. Subjects 5M3-LEZ and 5M4-MM produced mostly voiced /h/ in the context of moderate flow increases, while 5F1-HJ had both lower flow peak values and more cases of devoiced /h/. On the other hand, AF6-MP's consistent /h/ voicing is obviously related to her lack of an abductory gesture, and AF3-PC's high percentage of voiced /h/ is probably also best accounted for in terms of her low flow during abduction. Conversely, the high incidence of /h/ voicing breaks in AM1-RM may be related to his extensive flow increases compared to other men.

3.3 Direct comparison of voicing in /h, p, t/

As discussed in chapter 1, one of the underlying themes of this work is that analysis of /h/ can yield information on laryngeal activity and voicing thresholds that is relevant to understanding voicing patterns in stop consonants. This section makes direct comparisons between the /h/ and stop data to see what kinds of specific correspondences we can state. One should remember in this context that stop production is accompanied by an intraoral pressure increase, hence a drop in transglottal pressure. The expected effect of this is to make devoicing more common and/or extensive in the stops than in /h/.

As a starting point for discussion, Figures 3.13 combine the histograms for /p, t/ VOTs and for VOT_h into a single plot for each speaker. The men's data are given in Figure 3.13a. The salient feature, of course, is the high percentage of tokens with VOT_h=0. Obviously where we have a number of fully voiced /h/'s, we do not expect simple overlap of VOT_h and voiceless stop VOT distributions. The noncontrastiveness of /h/ voicing allows such disparities. What we can do is to compare the positive values of VOT_h (that is, the higher of the two VOT_h modes) with the stop VOT values. In the two men (AM1-RM and AM6-ED) who produced a number of devoiced /h/, we observe that VOT_h ranges are essentially coextensive with the stop VOT ranges. The women's data (Figure 3.13b) include more positive values of VOT_h. In the subjects with some number (but not 100%) VOT_h=0, the VOT_h distributions are generally overlaid on those of VOT for /p/, whereas /t/'s tend to be a bit longer. In the subjects who produced few or no cases of fully voiced /h/ (viz., AF2-MS, AF5-MD, AF7-LK), we actually seem to have a steady progression of VOT_h < VOT of /p/ < VOT of

/t/. Indeed, the factors usually credited for the /p/ < /t/ pattern (namely, increasing time to establish high transglottal pressure after an abduction peak) could also account for the location of VOTH on the continuum. Stop place differences are not as clear in the children's data as in the adults', but again the range of VOTH is essentially coextensive with /p/ and /t/ VOT ranges.

Summarizing over all speakers, we observe some fairly consistent correspondences between VOTH ranges and /p, t/ VOT ranges. One of the more obvious implications of this is that subjects with the longest values of VOTH tend also to produce the longest stop VOTs. Figure 3.14 shows this relationship directly, plotting each subject's maximum VOTs for /p/ and /t/ against his or her maximum VOTH. Overall, there is a shallow positive relationship that is significant for both comparisons: for /h, p/, $r=.643$, $p=.001$; for /h, t/, $r=.546$, $p<.001$. In both plots, the most extreme values belong to child subjects. To determine whether maximum VOTH reliably predicts maximum /p, t/ VOT in adults as well, correlations were recalculated using the adult data only. The results of this analysis were weakly significant for /p/ ($r=.523$, $p=.054$), and were in the right direction but did not reach significance for /t/ ($r=.403$, $p=.157$). Arguably, the subjects who produced fully voiced /h/ should be excluded from this analysis. Recomputing the correlations without these 4 subjects produces slightly stronger results (for /h, p/, $r=.688$, $p=.026$; for /h, t/, $r=.552$, $p=.1003$), but the smaller numbers make the result less reliable. In any case, a general positive trend does appear to hold across subject groups, perhaps with some variation in degree. A positive slope is also obtained when standard deviations for VOTH are plotted against those for /p, t/ (Figure 3.15), but in this case the trend owes entirely to the children. When all subjects are included, for the /h, p/ comparison, $r=.639$, $p<.001$; for the /h, t/ comparison, $r=.718$, $p<.001$.

Removing the child subjects, the /h, p/ results are $r=.203$, $p>.49$ and for /h, t/ $r=.002$, $p>.99$. As noted above, there are major production differences between /h/ and the stop consonants; one might well expect these differences to preclude any similarities between VOTH and stop VOT distributions. The fact that /p, t/ show significant correlations with /h/ at all suggests that, within an individual, some regularities hold among voiceless consonants as a class.

One may recall here a comment at the end of section 3.1 that significant correlations were also obtained for standard deviations of /p, t/ VOTs and stressed vowel durations. These relationships raise a general question: Do the /h/ data provide any new information, or are they simply another outgrowth of effects we have already seen (related, perhaps, to general durational properties of the person's speech)? To investigate this, correlational analyses were performed for medians, maxima and standard deviations of /p, t/ VOTs, VOTH, vowel durations, flow peaks, and pressures. The results are given in Tables 3.8. (Note that these tables include the statistics for the pooled data discussed above for Figures 3.14–15. Some of these results were also briefly mentioned in general terms near the end of section 3.1.) The tables show that r-values are higher among medians and maxima of /p, t/ than of /h, p/ or /h, t/. Standard deviations for the 3 consonants are comparable. As discussed for Figure 3.15, the correlations lose all significance when the child subjects are removed. Also, although /p, t/ VOT medians correlate significantly with vowel duration measures and with VOTH, medians of VOTH and vowel durations do not show a strong relationship.

3.4 Determinants of voicing onsets 1: Macroscopic analysis. Relating the percentage of fully voiced /h/ to subject characteristics

We have seen that the degree of /h/ voicing undergoes regular variation across individuals, and that some aspects of a subject's VOT_h distributions can be related directly to his or her stop VOT patterns. In the remainder of this chapter, we attempt to define more precisely the factors that favor voicing in /h/, first in terms of subject averages and then in terms of measurements made on individual tokens.

This section, using the averaged data, addresses the question of why some speakers show more voicing than others during /h/. Toward this end, we correlate prevalence of /h/ voicing (%VOT_h=0) with a number of speaker and voice characteristics. Since most of these measures were discussed in detail in chapter 2, they are described here only briefly. The values available for each speaker included the following: 1) Two body size measures, height and neck circumference. Height is expected to reflect respiratory system variables including lung capacities, and neck circumference is taken as a crude reflection of vocal-fold length (cf. section 2.3). 2) Three f₀ measures, referred to in the tables as Minf₀.avg, MidVf₀.avg, and Onsetf₀.avg (again, cf. discussion in chapter 2). Minf₀.avg is the minimum modal f₀ on sustained /a/. MidVf₀.avg is the average f₀ at the middle of the stressed vowel following /h/. The Onsetf₀.avg is taken for each token as the average over the first two measurable periods, with subsequent averaging over all tokens to yield a single value. Depending on the duration of any voicing break, the first measurable pulses will occur at various times post-peak, so differences in the onset f₀ across tokens and speakers reflect, in part, effects of measuring pulses at different times across the adductory phase.

These 3 f_0 measures were chosen to reflect various aspects of laryngeal behavior during speech, viz. conditions around abduction (the onset f_0), in stressed syllables (the mid-vowel f_0), and in absence of marked prosodic or coarticulatory influences (the minimum f_0 on sustained /a/). 3) Two measures of airflow: Pkflow.avg, the average smoothed airflow at /h/ peak, and ACflow.avg, taken as the average over the first two glottal pulses following the /h/ peak. Like onset f_0 , the AC flow measure necessarily incorporates effects of measuring pulses at various times post-peak. As discussed above, the peak /h/ airflow serves as an indication of the extent of vocal-fold abduction whereas AC flow reflects the vibrational amplitude of the vocal folds themselves. Lower AC flows may result from shorter vocal folds or from conditions that inhibit strong vibration, such as high longitudinal tension. 4) Peak intraoral pressure (Pres.avg) during /p/ closure. 5) The average laryngeal resistance (Resis.avg), calculated for each subject from the pressure and flow means given in the table (Resistance = Pressure/Flow). Resistance depends largely on glottal size but also varies with glottal shape and aerodynamic conditions, so it provides a broader index of conditions within the glottis than the peak flow measure alone (which we are using as an index of glottal width). Taken together, these measures provide information on many of the factors relevant for voicing: The length, mass, and tension of the vocal folds (under various speaking conditions), the extent of abduction, depth of vocal-fold vibration, subglottal pressure, and general aerodynamic conditions in the glottis.

Table 3.9 presents subject averages for the measures just described. Correlations among all the variables are presented in Appendix E. Tables 3.10 present the data in simplified form, with r-values reduced to a single digit and showing only cases where $p \leq .10$. Figures 3.16–3.19 plot the percentage of fully voiced /h/

(VOTh=0) as a function of the other measures, listing r-values for the pooled data and the 3 speaker groups, and showing the best linear fit for the pooled data when the regression approached significance. As discussed above, AF6-MP's /h/ voicing is probably best attributed to lack of an abductory gesture; arguably, her data point is not relevant to the current analyses, and it is shown unfilled in the plots to distinguish it from other women. Correlations of the pooled data performed with and without her gave quite similar results, so results are shown only for the analysis that excludes her. The decision whether to include her or not has most effect on the conclusions one draws for the adult female group.

Figure 3.16 shows the results for /h/ voicing as a function of the two body-size measures. As physical descriptions of our speakers and subject groups, height and neck circumference complement each other: Height separates the children clearly from the adults, whereas in terms of neck circumference the 3 groups constitute overlapping but fairly distinct populations. There is no clear relationship between /h/ voicing and height in the pooled data, but there does appear to be a positive trend among the men. For neck circumference, a weak positive relationship is again seen for the men and also for the group data ($r=.402$, $p=.08$).

Relationships with the 3 f0 measures are shown in Figure 3.17. The minimum f0 measure is not a useful predictor of VOTh, but there are weak negative correlations between VOTh and f0 at vowel midpoint ($r = -.417$, $p=.07$) and voicing onset ($r = -.440$, $p=.05$). These trends also appear in the adult male group, so that devoicing is more common in men who tend to use higher f0's during speech.

Figure 3.18 plots /h/ voicing against the two flow measures. There is no relationship with peak flow in the pooled data, but there are negative trends within both adult groups, suggesting that voicing breaks in /h/ are more common among speakers with greater average degrees of abduction. For pulse amplitude, a positive correlation appears in the 5-year-olds ($r=.831$) and is weakly present in the overall data as well, but any trends in the two adult groups are negative.

Figure 3.19 relates VOTh to the pressure and resistance measures. Pressure has no regular effect on VOTh in the adults or in the pooled data, but a positive relationship appears to hold in the 5-year-olds. The resistance measure is not a useful predictor of VOTh for the pooled data or for any subject group. The effect of dividing the flow by the pressure is basically to exaggerate the differences between subjects with lower and higher airflow rates.

To clarify further how speaker groups may differ in the factors associated with continuous voicing of /h/, Table 3.10 organizes the data according to speaker group and measurement type. Table 3.10a, showing correlations with %VOTh=0, summarizes Figures 3.16–3.19. As before, we observe that /h/ voicing in men is related positively to body size and negatively to f_0 and amplitude measures. Thus, continued voicing occurs most often in taller speakers, and less often in speakers with higher f_0 's and/or lower oscillatory amplitudes. In the women, /h/ voicing has a weak negative relationship to flow measures and possibly to body size; weak positive correlations may exist for f_0 . Assuming these trends are reliable, it appears that smaller physical systems reduce airflows, yield higher fundamental frequencies, and facilitate continued oscillation, perhaps because large glottal widths are not achieved. For the 5-year-olds, continued voicing is

associated with higher pressures and pulse amplitudes (the latter possibly a pressure effect itself).

Table 3.10b shows how well the speech measures are predicted by body-size variables. Height and neck measures are most closely correlated in the women and 5-year-olds, consistent with the laryngeal growth data showing size increases in the adolescent male out of proportion with general growth. Neck circumference is also related to f_0 measures more clearly in the women and 5-year-olds than in the men. Overall, f_0 and body-size measures are inversely related, and this is generally true within the 3 speaker groups but especially so among the children. For the summed data, there are weak positive correspondences between body size and airflow measures, but, interestingly, relationships within the 3 subject groups are negative. Body size and pressure appear to be positively related among the women; clear trends do not appear among the men or 5-year-olds.

For present purposes, the minimum f_0 measure does not seem particularly useful. Its relationships with body-size measures do not always run according to expectation (e.g., the positive correlation with height in women, Table 3.10b) and it is also least closely related to the other f_0 measures, especially among adults (Table 3.10c). All f_0 measures tend to be positively correlated with the two flow measures in the children and especially in the men. Surprisingly, both adult groups show negative relationships between f_0 measures and pressure levels, despite the usual association of higher frequencies and higher pressures. This atypical pattern may result from comparing f_0 variation across speakers rather than within individuals. The resistance measure also turns out to be of questionable value. It shows no clear pattern of relationships with the f_0

measures and, as Table 3.10d shows, is very highly correlated with peak flow in most subjects, and also with AC flow in the women. The current results may not be widely representative of laryngeal resistance measures. Most published values of laryngeal resistance are derived from adducted conditions, where peak airflows vary much less across subjects than they do in the /h/ peaks measured here.

Probably the most striking result of these analyses is the frequency with which relationships defined for the pooled data do not hold within individual subject groups. Moreover, we can define certain regular differences among the groups that could not be discerned from looking at the combined data (e.g., the differences in how f_0 measures are related to Peak and AC flow; cf. Table 3.10c). This implies that the factors affecting vocal-fold vibration differ somewhat across speakers and subject groups, a possibility implicit in the multidimensional phonation threshold pressure equations. Delimiting the range of values speakers use along these dimensions is the theme of the next section.

3.5 Determinants of voicing onsets 2: Microscopic analysis. Characteristics of voiced and devoiced /h/ within individual subjects

3.5.1 Introduction to the data

Since a number of factors can be manipulated to achieve oscillation, the possibility exists that speakers may differ in which adjustments they tend to rely on during running speech. The analyses in this section provide preliminary data on the parameters that correlate best with devoicing within single subjects. The general strategy is to correlate voicing break duration with the other token

measures. Notice that these token measures were the source of much of the averaged data discussed in section 3.4. The underlying questions of these two sections are rather different, however: Whereas in 3.4 we looked across subjects for the factors that correlated with a high percentage of voiced /h/, here we correlate voicing break duration with other variables to see what conditions favor devoicing within an individual speaker.

The following measures were available for individual tokens of /ha/: 1) VOT_h, in msec. 2) Peak flow, the amplitude at the peak of the /h/ abduction, measured in the smoothed signal. 3) AC flow. As described above, this was taken as the difference in flow between the lightly and heavily smoothed flow signals at pulse peaks and serves as an index of vibratory amplitude. The measure used for each token is the average of the first two glottal periods. 4) DC flow, measured in the smoothed signal, at the time of voicing onset. In tokens with voicing breaks, this measure may be interpreted as a threshold value for the flow rate and/or the extent of adduction at which sustained oscillation becomes viable. In tokens with no voicing break, it is heavily confounded with the peak flow. DC flow is therefore only considered for voiceless tokens, and there only briefly since it turned out to be largely redundant with other variables. 5) Onset f₀: the average f₀ over the first two periods of each token. A few tokens were excluded where measurement was complicated by intermittent pulsing or diplophonia. 6) Peak pressure during the /p/ closure.

Correlations among these variables yielded 21 matrices (one for each speaker) representing all tokens of /h/. Separate correlations were also performed on voiceless-only tokens in subjects who produced more than 10 tokens with VOT_h>0 (2 men, 5 women, 4 children). These matrices are presented in full in

Appendix F. Discussion here will follow various simplified versions and graphical overviews. Let us begin with some general observations. Table 3.11 condenses all correlational data onto one page, rounding r -values to single digits and showing only correlations where $p \leq .10$. Results of analyses performed on all tokens of /h/ are shown on the left side of the page. The right side shows results for voiceless tokens only. Subjects without matrices on the right side produced mostly fully voiced /h/. The advantage of this presentation is it shows global patterns in how variables are related to each other. For example, it shows that VOTH is correlated with both Peak flow and AC flow in many subjects: AM4-SL, AF5-MD, AF7-LK, 5M1-DJ, 5M2-SS, and 5F3-HH. More generally, the frequency of significant correlations indicates quite a bit of regularity to the VOTH behavior of a single speaker. Equally striking is the variety of individual patterns, both in terms of where the significant relations occur (which variables are involved) and in the strengths of the relationships (the r -values). This leads to a conclusion similar to that reached (by a rather different route) in section 3.4: The factors that correlate with /h/ voicing are not the same for all speakers.

Where subjects produced enough devoiced /h/ to yield a matrix on the right side of Table 3.11, we can also compare across voicing conditions. In some cases, the results are quite similar. For example, most (3 of 4) of AM1-RM's significant correlations remain roughly unchanged whether or not we consider the full data set (left side) or voiceless tokens only (right side). The one difference is that VOTH no longer shows a positive correlation with f_0 when the voiced tokens are removed. This suggests that tokens of /h/ with and without voicing breaks are differentiated, in part, by f_0 : Voiced tokens have lower f_0 's than devoiced tokens. This is true also for 5F3-HH. In contrast, AF5-MD shows positive

correlations with f_0 for both data sets. What differs for her is that the full data set shows a positive correlation between VOT_h and Peak flow which disappears when the voiced tokens are removed, suggesting that here cases of fully voiced /h/ tend to occur in the context of low flow peaks. More generally, where we observe differences in a speaker's two matrices, we can infer that the laryngeal conditions differ during voiced and devoiced productions of /h/. This is one example of a general hysteresis effect in vibratory systems, whereby oscillation persists for parameter values at which it could not be initiated (for theoretical discussion, see Lucero 1997). Baer (1975), using excised canine larynges, observed that for the same cross-sectional area, phonation could be sustained at pressures below those required to initiate phonation. Rothenberg and Mahshie (1988) reported that vocal-fold oscillations, and hence EGG signal strengths, were lower in amplitude for a given degree of opening during the adductory phase than the abductory. Glottal airflow simulations using a modified two-mass model also indicate that the requirements for initiating voicing are more stringent than those for maintaining it (McGowan et al. 1995). Another example of hysteresis in the current data was that voicing would typically resume at a lower flow rate (presumably indicating a smaller glottal width) than where it ceased before the /h/ peak. This phenomenon is visible in the VOT_h measurement sample figure (Figure 2.5, right side) and was discussed briefly in Koenig and McGowan (1996).

Although they provide a means of differentiating between voiced and voiceless tokens within a speaker, the correlation matrices in Table 3.11 do not distinguish speakers from each other on the basis of their VOT_h behavior. To show this clearly, Table 3.12 summarizes the correlation matrices for the 6 subjects with fully consistent /h/ voicing (either all VOT_h=0 or all VOT_h>0). Again, r-values

are rounded to a single digit and are shown only for corresponding $p \leq .10$; further, correlations with VOT_h are excluded, since for subjects with all $VOT_h = 0$ the VOT_h values did not vary at all. Although a number of patterns are evident in Table 3.12, they bear no relationship to /h/ voicing. Rather, they characterize the conditions around abduction in general, regardless of whether voicing continues or not. For example, 3 speakers show positive correlations between pressure and AC flow, indicating that larger vibrational amplitudes occur under conditions of higher driving pressures. Most subjects (all but AF2-MS) show significant or suggestive correlations between Peak flow and AC flow; the sign of the relationship varies, but not in correspondence with /h/ voicing behavior. The negative correlation may represent another pressure effect: Higher peak flows indicate increased glottal aperture, which could lead to a greater dip in subglottal pressure and/or reduced particle velocities within the glottis, either of which could have the effect of reducing vibrational amplitudes. The positive r -values for Peak \times AC flow are more difficult to explain. It is worth noting that in 1 of the 3 cases the correlation may actually not be very meaningful since it occurs in AF6-MP, who had very little variation in her flow peaks and seemed to rely more on voice quality changes than abduction to effect an /h/ (cf. section 3.2).

Lastly, 4 of the speakers show a positive $f_0 \times$ AC flow correlation. This may come as something of a surprise, since one might expect abduction to increase the passive vocal-fold tension and raise the vibrational frequency, giving /h/ high f_0 's and low AC flows (cf. Bickley 1991). Also, glottal stop and laryngealization are characterized by decreased f_0 and pulse amplitude (e.g., Dilley et al. 1996; Hillenbrand & Houde 1996); if these display the effects of vocal-fold adduction, we might expect to see opposing effects in /h/. But

Figures 3.20 and 3.21 show that most of the adults, including these 5, show an increase in both f_0 and AC flow coming out of /h/. Only one adult (AF7-LK) shows clearly higher f_0 during /h/, while two others (AF4-DB and AM3-DH) show level or slightly elevated f_0 . Among the 5-year-olds, however, one observes only a single good case of lowered f_0 during /h/ (5M3-LEZ). The most sensible explanation for a lowered f_0 around /h/ is, again, a decreased subglottal pressure around the /h/ abduction. The apparent age difference may indicate stronger (or more operative) pressure effects in adults and/or stronger stiffness effects in children. Differences among adult subjects may also reflect differential effects of these two variables.

3.5.2 Within-subject correlations and speaker group

Correlations among the average measures presented in section 3.4 suggested possible group differences in how voicing control parameters were related across individuals. Among the men, for example, voicing breaks occurred in the context of reduced vibrational amplitudes and increased f_0 , whereas among children devoicing was most likely given a combination of low vibrational amplitudes and lower pressures. To explore such differences further, the correlation matrices listed in Appendix F were broken down by speaker group and variable and are shown in Tables 3.13. The organization here is similar to that in Tables 3.10, but recall that the variable of interest there was each subject's %VOT_{h=0} whereas here it is the duration of voicing break around each /h/. Tables 3.13 thus complement Table 3.10.

Table 3.13a shows how peak flow, AC flow, onset f_0 , and pressure correlate with VOT_h within each of the 21 subjects. Consider first the positive correlation

between peak flow and VOT_h that occurs in 2 men, 2 women, and 4 children. For these speakers, voicelessness tends to occur in the context of higher flow peaks and greater abduction extents. Compare this with the conclusion derived from Tables 3.10: There, men and women with lower average flow peak amplitudes tended to show more cases of voiced /h/. Positive correlations between f_0 and VOT_h suggest that increased vocal-fold tension is a factor in achieving voicelessness for some speakers. In contrast, Table 3.10 showed that women with higher f_0 's tended to produce more cases of voiced /h/.

The results for VOT_h vs. AC flow are perhaps the most interesting. Relationships are significantly negative for 6 of 7 children and 2 of 4 men but significantly positive in 3 of 6 women. Apparently, vibrational amplitudes in the vicinity of an abduction gesture reflect somewhat different glottal conditions across speaker groups. Tables 3.13b–c offer further support for this conclusion, showing positive correlations between AC flow and Peak flow in most of the women, whereas no trend emerges among the men or 5-year-olds. Correlations between f_0 and AC flow (Table 3.13c) also vary across speakers. In particular, the relationship is positive in most of the men.

A final feature of Table 3.13 deserves comment. One may remember from section 3.2 that there was absolutely no relationship between subject median values for Peak /h/ flow and pressure (Figure 3.9). When we look at multiple productions by a single speaker, however, we observe positive relations in 7 of 18 subjects, though r -values remain modest as we would expect if /h/ flow peaks vary largely with differences in abduction extent.

The general conclusion to be drawn from Tables 3.13 is that voicelessness may be achieved in somewhat different ways by different speakers. Yet amid this variation it is still possible to discern some common patterns as a function of speaker age and gender. One should keep in mind that for some speakers the correlations with VOT_h describe only a handful of tokens; direct inspection of the data is therefore warranted. In the following section, individual productions by single speakers are examined.

3.5.3 Within-subject analysis of individual /h/ productions

The 15 subjects (4 women, 4 men, 7 children) who showed mixed voicing of /h/ provide information on the conditions under which voicing onsets and offsets occur. In those who produced primarily voiced /h/, inspection of voiceless tokens should help delimit the conditions that contribute most to voicelessness in these speakers. Conversely, occasional voiced tokens in subjects whose /h/'s typically have a voicing break can yield insight into the main factors that facilitate continued phonation in those speakers. For discursive reasons, we begin at the two ends of the continuum and then describe more mixed cases.

3.5.3a: The rare devoiced /h/

Consider first the 5 speakers who showed only a few cases of devoiced /h/: AM3-DH, AM4-SL, AF3-PC, 5M3-LEZ, and 5M4-MM. For these subjects, significant correlations with VOT_h reflect the behavior of a few outliers. Figure 3.22 illustrates this by plotting VOT_h in individual tokens against peak flow, AC flow, f_0 , and pressure (where available) in subjects AF3-PC (left) and AM3-DH (right). For AF3-PC, correlations with VOT_h (cf. Appendix F) were uniformly nonsignificant, but Figure 3.22 suggests that her devoiced /h/'s did not occur

randomly. Two of the 3 fall at the high end of her /h/ flow peak range, and one of them also falls at the low end of the AC flow range. In this speaker, we may infer that devoicing tends to occur in the context of greater abduction and reduced pulse amplitudes. Subject AM3-DH had a positive correlation between VOT_h and f₀, and his scatter plots confirm that 2 of his 4 devoiced tokens have very high f₀'s. They also indicate that low AC flows are characteristic of devoiced tokens. More generally, we observe in both subjects that the rare voiceless token is often an outlier on one or more of the other measured dimensions. Also, we note that at the level of individual tokens, similar patterns are seen for AM3-DH and AF3-PC despite the differences in their correlation matrices.

Tables 3.14 attempt to formalize the notion of 'outlier' in these speakers with few devoiced /h/'s. Within speakers, percentile scales were obtained for each measure and compared with the measured values of that speaker's voiceless tokens. Cases where the token fell below the 10th percentile are indicated with L and those above the 90th percentile are indicated with H. Values below the 25th percentile (labeled *l*) or above the 75th percentile (labeled *h*) may also be informative. The 5 subjects under discussion here are those above the double line break. Tables 3.14 show that in all but a few cases (e.g., token #2 for AM3-DH), the rare voiceless tokens show extreme values on at least one other dimension. Moreover, we can discern some general patterns: Namely, the devoiced /h/'s are typically characterized by high peak flows and/or low AC flows. In the children, voicing appears to be most consistently related to AC flow. The children also seem to favor low f₀'s in their devoiced tokens rather than the high f₀'s seen in some of the adults.

The two speakers below the double line follow similar trends despite their higher proportions of devoiced /h/. Their scatter plots are given in Figure 3.23. For AM1-RM (left side of figure), increased f_0 is the main distinguishing feature of devoiced /h/. In subject 5F2-EC (right side), /h/ voicing is related primarily to AC flow and pressure and shows no clear effects of f_0 . In this case, the patterns are more easily observed in the scatter plots than the tables, mainly because she did not have many analyzable tokens. In general, the strategy of identifying the minority voicing type in terms of statistical outliers becomes less useful as the proportions of voiced and voiceless tokens become more equal.

3.5.3b: The rare voiced /h/

Consider now the 3 subjects whose /h/'s were usually devoiced: AF4-DB, AF5-MD, and 5F3-HH. Their token percentile values are given in Tables 3.15 (above the double bar) and a representative scatter plot, for AF4-DB, is given in Figure 3.24 (left). Here the question is what conditions give rise to the occasional voiced /h/, and the percentile tables show cases of $VOT_h=0$. Table 3.15 indicates that voiced tokens tend to have low f_0 's and pulse amplitudes and possibly low /h/ flow peaks as well. Lower f_0 is the most consistent feature across subjects. In AF4-DB, high pressures also tend to characterize the occasional voiced /h/. The AC flow effects differ across speakers in a way that is difficult to interpret. Subject 5M1-DJ, shown below the double bar and on the right side of Figure 3.24, had higher proportions of voiced /h/, but follows trends observed in subjects with only a few cases of voiced /h/: Namely, onset f_0 's and /h/ flow peaks are lower during the voiced /h/. DJ also shows consistently high AC flow for voiced /h/, similar to the other child subject in this group (5F3-HH).

3.5.3c: Subjects with mixed /h/ voicing

Three remaining subjects had roughly equal proportions of voiced and voiceless tokens: AM6-ED, 5M2-SS, and 5F1-HJ. Tables 3.16 give token percentile values for these subjects (showing voiceless tokens), and Figure 3.25 gives scatter plots for 5F1-HJ. Since the tables list voiceless cases, we expect patterns similar to those in Tables 3.14. In fact, the counts at the bottom of the table indicate that the same types of relationships are operative here, namely, voicelessness is accompanied by low AC flows, high peak flows, and usually high f_0 's (HJ's f_0 results are equivocal). It is, however, clearly more difficult here than previously to state concisely the distinguishing features of a subject's devoiced /h/, based either on the percentiles or on the scatter plots. As noted above, the more balanced a subject's VOTH distribution, the less appropriate it is to characterize one category in terms of extreme values and the more difficult it is to state general relationships among variables without more complex statistical procedures requiring many data points from each speaker to sort out the interrelationships reliably.

The foregoing discussion has tacitly assumed that these inter-speaker differences are, in fact, differences of subject rather than setting. That is, we have taken the experimental utterances as a general reflection of an individual's characteristic speech behaviors. A more likely possibility is that a speaker selects from a range of behaviors. The last speaker presented here, AF1-DR, provides limited evidence for what we may tentatively call different laryngeal settings. The scatter plots for this subject are comparable to those of 5F1-HJ in that strong regularities are difficult to discern visually, so it is preferable to work from the token percentile charts given in Table 3.17. The table lists cases of voiced /h/ since those were less numerous, and shows tokens in their order of production

during the experimental session (this subject did 3 sets of /h/-containing utterances during the course of the recording session). Table 3.17 shows that there are two different patterns to this subject's voiced /h/'s. One is characterized by moderately high f_0 's, flow peaks, and AC flows but low pressures; the other set shows low values of Peak flow, AC flow, and f_0 , consistent with what we observed in other subjects. Based on the high AC flows in the first set, it appears that voicing in these tokens was strong enough to continue despite extensive abduction and fairly high tension in the vocal folds. Most interesting, perhaps, is the fact that the two combinations of features break out neatly according to time of recording. At some point in the recording session, DR evidently changed certain laryngeal or aerodynamic parameters (including, apparently, speaking pressure levels) such that voicing in /h/ came to be associated with a different combination of conditions. At the same time, this subject provides evidence that a speaker's behavior over short time frames can be fairly consistent, since the tokens occurring midway through and late in the recording session were produced some 10 to 15 minutes apart.

4. Discussion

4.0 Overview

The organization of this chapter follows that of chapter 3, taking each of the several results sections in turn. The stop VOT data (section 4.1) confirm previous observations of children's data, and raise the possibility of gender differences in adults. The /h/ data in sections 4.2 suggest that 5-year-olds do not yet have consistent patterns of abduction and voicing, even when no coordination with supralaryngeal activities is required. The greater prevalence of voiced /h/ in men can be largely explained in terms of the phonation threshold pressure. Section 4.3 addresses some of the larger implications of these findings: To the extent that developmental trends in VOT reflect growing mastery over conditions at the larynx itself, decreasing VOT variability cannot be used as a general metric of interarticulator timing control. Theoretical perspectives on variability in children's speech are discussed briefly.

Section 4.4 reviews how body-size measures, VOT_h , f_0 , pressure, and flow measures were correlated across subjects, and considers the general issue of cross-subject variability in measures of laryngeal function and how they relate to one another. The cross- and within-group differences in voicing control parameters discussed in section 3.5 bear on some long-standing debates about f_0 control and the use of longitudinal tension in the vocal folds to effect devoicing. Global observations about age and gender effects and individual variability are given along with general conclusions in chapter 5.

4.1 Discussion of Section 3.1: VOT in the stop consonants

All adult and 5-year-old subjects produced highly significant VOT differences for each voiced-voiceless pair. The children's results follow previous developmental studies showing productive VOT contrasts in children as young as 2 to 3 years (e.g., Kewley-Port & Preston 1974; Smith 1978). Based on such results, some authors have concluded that VOT distinctions are acquired during a child's first few years (Davis 1995; Macken & Barton 1980). At the same time, researchers focusing on phonetic description have recognized that some details of children's VOT distributions do not become adult-like until much later. Thus, older children continue to show increased variability relative to adults and more category overlap, even though mean durations may be comparable (Barton & Macken 1980; Eguchi & Hirsh 1969; Gilbert 1977; Kent & Forner 1980; Kewley-Port & Preston 1974; Ohde 1985; Ostry et al. 1984; Zlatin & Koenigsknecht 1976). The current data support these earlier findings, and also confirm that children's aspirated stop production may be distinguished by occasional tokens with very long voicing lags. The children were more variable than adults even after correcting for durational differences, so that statistical artifact or general rate effects cannot be held responsible (cf. discussion below in section 4.3).

It is a well-established result that durational measures are often longer in children's speech than adults' (e.g., Hawkins 1973, 1979; Lee et al. 1997; Smith 1978). The current 5-year-olds did not show longer durations across the board, however. Rather, effects were limited to the unstressed vowel, where only 4 of the 7 children provided analyzable data. It has been stated elsewhere that the phonetic effects of stress (or syllable reduction) may be more limited in

children than adults (e.g., Allen & Hawkins 1980; Barton & Macken 1980; Pollock et al. 1993). The data obtained here suggest that children may fall into two groups with respect to syllable reduction. One group (represented by the children with measurable vowel intervals) does not achieve an adult-like durational contrast between stressed and unstressed syllables, but maintains enough articulatory detail to permit defining gross acoustic boundaries between consonantal and vocalic regions. In the other group, a more extreme durational contrast between stressed and unstressed syllables may be achieved at the expense of articulatory and acoustic differentiation between consonants and vowels within reduced (unstressed) syllables.

An hypothesis in the present work is that a sufficiently large quantity of data might reveal subtle gender differences in adult VOT distributions. The traditional VOT literature has been essentially silent on this matter. Typically, VOT studies have simply combined men and women from the outset, and those that have tested for gender effects explicitly (e.g., Zlatin 1974) have usually just reported a lack of significant effects and gone on to present only pooled data. The possibility of a gender effect on closure voicing receives brief mention in Keating (1984), who comments in a footnote that men's larger average supralaryngeal volumes should accommodate a translaryngeal pressure differential for a longer period of time (assuming comparable subglottal pressures). Similarly, Smith (1977) argues that the low incidence of closure voicing in young children may reflect the difficulty of maintaining a sub-supraglottal pressure difference during a closure when oral cavity volumes are very small.

Aerodynamic conditions in the upper vocal tract may be relevant to the voiceless stops as well. All other things equal, subjects whose vocal tracts have smaller cross-sectional areas should experience slower dissipation of intraoral pressure after a constriction release. Slower pressure discharge should lengthen the time needed to re-establish the requisite translaryngeal pressure differential and lead to a longer voicing delay after consonantal release. Klatt (1975; see also Menyuk & Klatt 1975) used similar reasoning to explain findings of shorter VOTs in singleton stops than in stop-liquid clusters (in the latter case, the "VOT" duration is the devoiced portion of the liquid). That is, since consonants like [ɾ] and [l] generally involve greater articulatory constriction than vowels, average rates of pressure discharge should be slower in stop-liquid clusters than in stop-vowel sequences. There has also been some debate that stop VOTs may be affected by following vowel height, with higher vowels conditioning longer VOTs, again as a cavity-size effect (e.g., Keating 1984; but see also Weismer 1980). Klatt (1975) obtained such a vowel effect but in this case he attributed the difference to laryngeal height and posture rather than to rate of pressure release.

The present data offer an additional, purely laryngeal reason to expect differences in VOT values as a function of age and gender. Namely, the results on /h/ voicing indicate that men are generally more likely than women or children to show voicing throughout abduction for consonants. If this effect is really laryngeally-based and independent of coincident upper vocal tract changes, we would expect men to show the shortest intervals of devoicing, i.e., the shortest VOTs. Along somewhat similar lines, Fant (1993)¹ has observed that Swedish-speaking women produce relatively more

¹ Thanks to G. Fant for bringing this article to my attention.

preaspirated stops than men, and that averages over long speech samples show a higher proportion of voiceless time for women than men. He raises these points during a discussion of gender differences in voice quality and the laryngeal factors that may give rise to them. If we follow this notion further, then the longer devoiced intervals during /h/ and slightly longer aspirated stop VOTs among our adult females may arise from the same factors that are thought to yield a greater tendency toward breathy voice in women than men. In this context, it is interesting to recall the scattered reports of breathiness in children's voices (cf. section 1.5, above). Much remains to be learned about voice quality factors during development, but if it is generally true that children show somewhat breathy voices also, then perhaps they differ from men in the prevalence of /h/ voicing for the same reasons that women do. That is, population differences in voice quality, in /h/ voicing, and in VOT means or ranges for aspirated stops could all be interrelated phenomena.

The present data do not provide direct support for a gender effect on VOT, but they do not speak strongly against one, either. The insignificant trend toward shorter VOTs in men than women or 5-year-olds is in the direction predicted by the above considerations; moreover, for the adults this trend cannot be attributed to a simple speech rate effect since vowel durations for the men and women are virtually equivalent. Ryalls et al. (1997) have recently reported significant gender differences in VOT of a magnitude similar to those seen here. Continued study is needed on how distinctive laryngeal contrasts are manifested within various populations of speakers. Where linguistic distinctions are involved, effects will probably be subtle, so demonstrating reliable effects may require substantial quantities of data from

many speakers. Although the number of /p/ productions analyzed here was fairly large (c. 1,000), the number of subjects may have been too small to reveal group differences.

4.2.1 Discussion of Section 3.2.1: Characteristics of abduction for /h/

Following previous studies of oral airflow variation in running speech (Gobl 1988; Klatt et al. 1968; Löfqvist et al. 1995; Rothenberg 1972), the DC flow contour was used here to infer abduction behavior for /h/. The average Peak flow values obtained for /h/ are generally consistent with the existing literature. Peak flows were significantly higher in the men than in the 5-year-olds, and somewhat higher in the men than in women, but extensive inter-subject variability among the women precludes any simple statement of gender effects. Higher flows in men are expected from lower resistances corresponding to larger glottal apertures. Variation in peak flows may also reflect differences in abduction extent across subjects. Values of intraoral pressure, measured from the unstressed (fourth-syllable) /p/, were also comparable with previous reports. Group differences in pressure values did not reach significance, but they did show the expected trend toward higher values in children than adults (cf. Bernthal & Beukelman 1978; McAllister & Sundberg 1996; Netsell et al. 1994; Stathopoulos 1995; Stathopoulos & Weismer 1985b).

Overall, the 5-year-olds showed greater within-subject variability than the adults. For peak flow amplitudes, the children had higher coefficients of variation ($CoV = \text{standard deviation} / \text{mean}$) but comparable standard deviations (SDs), while for pressure measurements, children had both higher

SDs and CoVs. These results add to the body of literature showing that high token-to-token variability characterizes children's speech, not only for temporal measures but also for postural and kinematic ones. Further, whereas most of the adult speakers had a stereotypic abduction pattern that retained a fairly stable form over changes in amplitude or duration, most of the 5-year-olds showed extensive variability in the rates of ab/adduction and even in the mere occurrence of abduction (that is, some children did not consistently produce a flow peak during /h/). The children also showed more frequent two-stage (non-monotonic) abductions than the adults. It has been argued that the devoicing gesture for speech has a standard cyclic form for all voiceless segment types, and a fairly constant duration of some 100–125 msec (Hertegård et al. 1995; Keating 1984; Klatt et al. 1968; Rothenberg 1972; Rothenberg & Mahshie 1988; Weismer 1980). In the current data, this characterization is generally appropriate for the /h/'s produced by adults, but does not accurately describe the children's productions. It appears that consistent abductory gestures must develop, either out of maturational processes and/or learning. Possibly, context-sensitive scaling of abduction (whereby, e.g., fricatives have greater degrees of abduction than stops) also develops with time. We return to the issue of cross-segment variation in abduction below.

4.2.2 Discussion of Section 3.2.2: Voicing of /h/

Although voicing of /h/ has been discussed for many years in qualitative terms, this appears to be the first time it has been given quantitative analysis. The VOTH results support previous claims that voiced /h/ occurs often during running speech, but they also reveal considerable cross-speaker

variation and some group trends. In an intervocalic, stressed position, fully voiced /h/ is most common among adult male speakers. In fact, many of our men produced nothing else. Some previous researchers (Lindqvist 1972a, b; Rothenberg & Mahshie 1988; cf. also Sawashima 1968; Sawashima & Hirose 1983), using data recorded from (as it happens) adult male speakers, have argued that cessation of voicing in running speech should not be expected to occur with abduction alone, but only when there is a concurrent upper vocal tract constriction. This assertion may be justified for men, but it loses validity when the subject pool is expanded to include female and child speakers, in whom patterns of /h/ voicing are much more mixed. Some fully voiced tokens of /h/ occur in every one of the 5-year-olds, but the frequency varies considerably across individuals, whereas among the women, voiced /h/ is common for some speakers, occurs occasionally for others, and is rare or nonexistent for others.

Voicing of /h/ is neither contrastive nor a known sociolinguistic variable in English. Moreover, the tendency for men to produce fully voiced /h/ apparently holds in languages other than English (viz., Lindqvist's subjects were speakers of Swedish and Sawashima's were Japanese). Based on these considerations, it seems unlikely that the age and gender effects on VOTH distributions result from social or other speaker-selected characteristics. Rather, they probably reflect group differences in physical conditions at the glottis. It is instructive in this context to review the aerodynamic requirements for voicing, as expressed in the phonation threshold pressure equation (repeated here from section 1.2):

$$P_{th} = cBx_0k_t/T$$

[c=coupling stiffness, B=damping, x_0 =glottal half-width,
 k_t =translaryngeal pressure coefficient, T=vocal fold thickness]

When P_{th} is lower, voicing can be initiated with less pressure, or force. Conversely, conditions that raise P_{th} (e.g., higher coupling stiffnesses, wider glottal apertures) allow voicing over a higher, narrower range of pressures. As discussed above (section 1.3), the age- and sex-related variation in the factors of this equation can be considerable. In particular, men are distinguished from women and prepubescent children by having longer, thicker vocal folds with lower stiffness. Added tissue bulk in men may also contribute to a greater glottal convergence angle, another factor that may reduce voicing threshold pressures (cf. eq. 3 in chapter 1). Lower stiffnesses, higher thicknesses, and greater convergence should all have the effect of lowering the phonation threshold pressure, or, for a given phonation threshold pressure, allowing voicing over a wider range of configurations (i.e., glottal apertures). The general prediction is that adult male speakers will tend to voice under conditions where women and children do not, and conversely, that women and children will devoice where men continue to voice. The VOTH data bear these expectations out.

The phonation threshold pressure equations thus offer some explanations for why men tend to show more voicing during /h/. The differences between the women and 5-year-olds in VOTH patterns are neither as easily stated nor explained. If we again assume that lower P_{th} indicates greater likelihood (or “ease”) of voicing, then the higher proportion of voiced /h/ in the 5-year-olds than in the women could imply any or all of the following:

Lower values of c (stiffness),
 B (damping—this is equivalent to decreased
viscosity, or higher water content),
 x_0 (the glottal half-width),
 k_t (the translaryngeal pressure coefficient),
and/or
higher values of T (vocal-fold thickness).

It is especially difficult to make predictions about tissue characteristics (viz., stiffness and composition) across groups. Potentially relevant variables include development of the vocal ligament, increasing fiber density in deep layers of the lamina propria, and thinning of the outer mucosal layer of the vocal fold (Bosma 1975; Goldstein 1980; Gray et al. 1997; Hirano et al. 1983), and direct data on these parameters are either sparse or nonexistent. Educated speculation is somewhat easier for the other factors. It seems unlikely, for example, that vocal-fold thickness is greater in children than in adults of either sex. On the other hand, it is quite possible (or probable) that average cross-sectional areas are smaller in children; this is consistent with the trend toward increasing speech airflow rates with age. Precisely how this might contribute to differences in /h/ voicing is not clear, however. If variation in glottal aperture were primarily responsible for individual differences in /h/ voicing, then across subjects we would expect an inverse relationship between peak flow rates and percentage of $VOT_{h=0}$. Such a trend seems to hold for the women (cf. Figure 3.18), but not for the children. It is also possible that k_t differs between children and women, but in this case the expected effect runs in the wrong direction. As discussed in chapter 1, modeling experiments (Scherer & Guo 1991) show k_t close to 1 for areas larger than $.05 \text{ cm}^2$, then rising rapidly as areas get smaller, so for adult-child comparisons the question is essentially whether we need to assume an appreciably higher k_t in the children. Using normative data, we estimated

that $.05 \text{ cm}^2$ was toward the low end of values predicted for children, so for abducted conditions we assumed roughly constant k_t across subject groups (cf. Appendix A and discussion in section 1.2). Since many children do not seem to abduct extensively for /h/, however, that assumption may not be valid and average k_t 's may be higher among 5-year-olds than adults. But increased k_t should drive phonation threshold pressure up, and make voicing occur under more limited circumstances in children than women—just the opposite of what the VOTh data show.

A remaining possibility is that differences in /h/ voicing between women and 5-year-olds reflect aspects of vocal-fold vibration that are simply not captured by the current measures. There have been occasional reports of differences in voice source properties between children and women; for example, Sapienza and Stathopoulos (1994) found that the time of maximum flow declination occurred earlier in (the closing phase of) the glottal cycle in women than in either men or 4-year-olds. This finding implies subtle group differences in the velocity profile of the glottal pulse and in the vibratory behavior of the vocal folds, factors which could conceivably affect voicing threshold values. Laryngeal modeling is only beginning to reach a stage of sophistication where one can make systematic inquiries into such possibilities. Pending more detailed work in this area, it is not unreasonable to suppose that developmental changes in vocal-fold tissues and in laryngeal control might have some effect on vocal-fold vibratory behavior.

Theoretical descriptions of vocal-fold vibration indicate that a number of parameters can be manipulated to achieve phonation, even in simplified systems like the two-mass model. Without further data it is not possible to

pinpoint exactly which laryngeal and aerodynamic factors are most responsible for producing the observed differences in /h/ voicing. It is also not possible to tell whether subject differences in VOTH arise from necessary, inherent conditions or from alterable settings. Although /h/ voicing itself probably does not carry sociological significance, it may be secondarily affected by parameters like voice quality or f0 level, which do. The fact that one speaker, AF1-DR, displayed two different /h/ voicing patterns is one bit of evidence that speakers operate within a range of possibilities and can select among various options. What we can assert with confidence from these data is that a characteristic abduction gesture yields varying degrees of voice suppression in speakers varying in age and gender. If there is any consistency to an individual's abduction patterns across different speech sounds, this fact alone has general implications for the management of distinctive voicing contrasts, suggesting that speakers may adopt production strategies in accord with the physical conditions that exist at the glottis.

4.3 Discussion of Section 3.3: Direct comparison of voicing in /h, p, t/

The other group effect on VOTH was a wider range of values in children than adults, reflecting occasional productions of /h/ with very long voicing breaks. In fact, the children with the highest values of VOTH were the same ones who produced the longest VOTs in /p, t/. Adult subjects also seemed to show a correlation between maxima of VOTH and /p, t/ VOT, but the relationship was less clear owing to a restricted range of values and the number of subjects who produced only voiced /h/. Within subjects, ranges and central tendency measures for /p/ VOTs were strongly correlated with those of /t/; weaker but reliable correlations were seen for /p, t/ VOTs vs. VOTH and vowel duration.

Correlations between VOTH and vowel duration were weak or nonexistent, however, suggesting that voicing break durations for /p, t, h/ are not related via a simple factor such as speech rate. Manuel and Stevens (1989) observed that addition of /h/ did not seem to increase duration of a phonetic (vocalic) string, so that, apparently, /h/ consists of superimposing a laryngeal maneuver on the concurrent upper vocal tract activities required for other surrounding sounds. In this context, we may interpret the range of voicing break durations that encompasses both VOTH and the stop VOTs as a reflection of their common laryngeal production component. In the 5-year-olds, standard deviations for VOTH and stop VOTs were also reliably correlated, suggesting that VOT variability should be attributed in some measure to these same laryngeal factors. In the adults, on the other hand, variability in voiceless interval duration is governed by different factors in the stops than in /h/. The most likely candidates are interarticulator timing and the vocal tract pressure changes induced by oral constriction.

There is a possible objection to using VOTH data as a source of information on laryngeal control for distinctively voiceless sounds, however. Namely, one could argue that since voicing in /h/ is noncontrastive, speakers simply do not constrain their laryngeal behavior for /h/ as they do for consonants in which voicing is distinctive. The difficulty with this argument for the present data is that children's voiceless stops appear to demonstrate variability in control rather than constraint. Indeed, defining the sources of this variability has been a major goal of developmental speech research. According to traditional accounts, the degree of glottal abduction at the instant of stop release is a primary determinant of VOT duration in adults (e.g., Lindqvist 1972b, but see Löfqvist 1992 for some qualifications). It has

been supposed that abduction extent remains fairly constant while the timing of release relative to the peak varies. Assuming that children obey similar physical principles, it is reasonable to hypothesize that the high standard deviations seen in children's VOTs may reflect variation in abduction extent at the time of release.

In the current data, however, the children with wide VOT distributions also produced a wide range of voicing break durations in /h/, where laryngeal setting is really the only thing that needs to be controlled. To reject the possibility that abduction degree contributes to VOT variability would be to assert that these children impose greater control over abduction degree - during stop production than they do during /h/, even while variability in relative timing remains (as the source of high standard deviations). In other words, this ascribes all VOT variability to variation in temporal phasing and none of it to variation in abduction degree (or other voicing control factors). Given that laryngeal behavior is hidden both visually and auditorily during stop closures and only becomes apparent upon release, it is difficult to imagine on what basis a child might establish such a pattern. That is: Why would children adopt more consistent laryngeal behavior during a stop closure if not to achieve an acoustic result more like adults' on release? Furthermore, it is not the case that /p, t/ VOTs show lower degrees of variability than VOT_h, as one would expect if more precise control were being imposed on the stops. Standard deviations for the 3 measures are comparable and even correlated across subjects.

One could conceivably argue for a developmental progression whereby (laryngeal) movement extents become stable before relative timing does. This

is certainly a testable hypothesis. Detailed investigation into this question would require measures and speech materials rather different from those used here, however (e.g., one might vary speech rate and loudness systematically to induce a range of abduction magnitudes and articulatory durations). The current data provide no direct support to this suggestion; if anything, the variability in the 5-year-old's /h/ flow peaks would require further explanation under this account. A general trend that effects movement extents as opposed to timing is, to all appearances, motoric rather than linguistic, so one would expect it to apply to all sound types regardless of whether voicing is contrastive or not. It is certainly not clear *a priori* why abduction degree should become stable in stops before /h/, especially given the more complex articulatory requirements of the stop consonants.

Another explanation for the /h/ flow peak variability is that young children, aware that full abduction is not necessary for /h/, adopt a strategy similar to AF6-MP's. The children with widely varying /h/ flow peaks might then be in a state of transition from minimal to more extreme abductory movements, a stage experienced by most but not all speakers (MP being a case in point). This explanation essentially says that children have a bias in their laryngeal behavior. Again, this is a possibility worth considering, but the available data hardly justify settling on this conclusion. Further, one might expect such a predisposition to have wide-ranging effects on voiceless consonant production, and not be limited just to /h/.

The assumption underlying all VOT literature, including cross-population comparisons, is that the abduction maneuver is essentially a constant, unitary event that does not vary in any significant way across repetitions of the same

sound sequence. In adult speakers, where /h/ flow contours usually assume a fairly regular shape, this traditional account of VOT variation is sensible, and intra-speaker variation in VOT is easily interpreted as a reflection of phasing changes between otherwise consistent laryngeal and oral gestures. But stable abduction gestures apparently do not usually develop by 5 years of age. The most parsimonious explanation for the 5-year-olds' data is that the variability and prevalent voicing observed in the children's /h/'s are also characteristic of the voiceless stops. It is possible that the laryngeal component is even sufficient to explain most salient aspects of children's voiceless aspirated VOTs, so little recourse to interarticulator timing variability is necessary. At the very least, laryngeal control needs to be recognized along with temporal coordination as a substantial source of variability in consonant voicing measures, including VOT.

As discussed in chapter 1, VOT studies have been a major focus in developmental descriptions of speech production, and there has been considerable debate over what increased variability may tell us about the speech acquisition process. Statistical artifact and/or measurement error can apparently not be held solely responsible (cf. Chermak & Schneiderman 1986; Kent 1976; Kent & Forner 1980; Ohala 1975; Rimac & Smith 1984; Smith 1978, 1994; Smith & McLean-Muse 1986); working from this assumption, a number of explanations have been proposed (for a concise theoretical review, see Sharkey & Folkins 1985). Probably the most widely espoused view within the speech literature has been that speech production is a case of motoric skill learning, in which higher variability, longer movement durations, and slower reaction times are all seen as characteristics of motoric inefficiency. This is gradually alleviated as movement planning becomes more

stereotyped and cohesive and as the neuromotor system itself becomes more elaborated and efficient by means of cell and axon proliferation, myelination, stabilizing EEG patterns, etc. (Ferguson 1986; Hawkins 1979; Kent 1976; Kent & Forner 1980; Netsell 1981; Rimac & Smith 1984; Smith 1978, 1994; Smith, Sugerman & Long 1983, Tingley & Allen). Accordingly, age-related decreases in the variability of aspirated stop VOTs have been taken as one index of general neuromuscular maturation.

Certain difficulties with this account have been noted (Kent & Forner 1980; Smith 1995; Stathopoulos 1995; Tingley & Allen 1975). One is that, although children as a group usually show higher average standard deviations than adults, there is typically some overlap between groups, so that variability cannot be taken as a reliable performance index of (age-related) neuromotor development. Also, individual children may show extensive variability on one measure but not on others. For example, Stathopoulos (1995) measured sound pressure level (SPL) and a number of presumably related parameters, including f_0 , intraoral pressure, airflow, and respiratory volumes (via lung and rib cage displacements), in 4- to 12-year-old and adult speakers. Although the younger children did show higher variability than adults on various measures including SPL, the variability of the composite parameter SPL could not, in general, be easily predicted (e.g., by an additive procedure) from the variability observed in the various related parameters. Voicing, like SPL, is multiply-determined, and parallel examples can be found in our /h/ voicing data. Subject 5M1-DJ is an instructive example: Although he had high standard deviations for VOT and VOT_h, his /h/ flow contours and peak values were quite consistent compared to most of the children. In DJ, then, the degree of abduction variability showed no clear relationship to the

variation in voiceless interval duration. Interestingly (and maybe not surprisingly), his correlational and token analyses indicated that VOTH was most strongly related to f_0 and AC flow variation. The implication is that valid interpretation of voicing data, especially its variability, requires concurrent information on a number of related parameters. More generally, researchers need to consider carefully what level of production is appropriate for measurement when multiple parameters can be manipulated to achieve a certain end.

Issues such as these have lent some support to an alternative view of variability proposed by Thelen (1989; see also Thelen & Studdert-Kennedy 1991). Here, variability is seen as an adaptive reorganizational strategy for dealing with changing physical system. Cross-subject and cross-articulator differences in variability measures are then to be expected as individuals choose unique motoric patterns for achieving their desired ends. This perspective can easily accommodate the current data. Unequivocal support, however, can only come from longitudinal within-subject studies making measurements of motor behavior along with anatomical and physiological parameters in individual subjects. Such elaborate work has yet to be done.

The group patterns observed for VOTH do force us to one conclusion: The degree of voice suppression a speaker achieves by a characteristic abduction maneuver does not remain stable through development, and a child must therefore adjust for changing laryngeal conditions over time. The adolescent voice change in boys means that some age and sex effects on laryngeal parameters are inherently confounded. Thus, although VOTH distributions varied by speaker group, it is difficult to parcel out pure age and sex effects.

Characteristics of the adult male group can be attributed to their unique laryngeal structure; the differences between the women and the 5-year-olds apparently reflect some combination of glottal aperture size and vocal fold structural characteristics. Group differences in the patterns of correlations among VOT_h, f₀, pressure, and flow values offer additional support for the notion that children and adults use somewhat different strategies to effect voicing and devoicing. Variability in stop VOTs can be ascribed to a variety of causes, but high VOT_h variability can only mean that control of voicing onsets and offsets is not adult-like in 5-year-olds. This implies that developmental change in VOT cannot be interpreted as a simple metric of changing interarticulator timing skill.

4.4 Discussion of Section 3.4: Relating the percentage of fully voiced /h/ to subject characteristics (macroscopic analysis)

As a first step toward defining the laryngeal and aerodynamic conditions in our 3 speaker groups, relationships were explored between /h/ voicing and a number of other variables for global patterns across subjects and then at the level of individuals. Although correlational analyses such as this cannot establish causality, they do indicate strengths of relationships among variables and provide focus for further work.

The two body-size measures, height and neck circumference, were moderately predictive of the frequency of voiced /h/ in men. In addition to being physically larger, men with mostly voiced /h/ tended to show lower average f₀'s and lower peak flows. The weak correlations observed for women followed a rather different pattern: Here, /h/ voicing was more common in

smaller speakers with lower peak flows but higher f_0 's. Neither body size nor peak flow served to predict the frequency of voiced /h/ in children. Instead, children were more likely to voice throughout tokens of /h/ showing higher pressures and pulse amplitudes. In adults, relations between /h/ voicing and pulse amplitude were either negative or nonexistent.

Sawashima et al. (1983) reported that vocal-fold length correlated fairly well with neck circumference in women and with minimum modal f_0 in men. In the current data, minimum f_0 did not really predict anything, whereas neck circumference showed a positive relationship with /h/ voicing in men but not in women. In general, f_0 measurements were better correlated with each other and with aerodynamic measurements in the men and 5-year-olds than in the women. It appears that f_0 may be differentially sensitive to some influences in the 3 speaker groups. On the other hand, the three f_0 measures were most closely related to each other in the children, suggesting that children may have somewhat limited options for varying f_0 within the ranges defined by their physical systems. Limitations could derive in part from incomplete vocal-fold tissue differentiation and a developing vocal ligament (cf. Bosma 1975; Hirano et al. 1983).

In general, relationships among the aerodynamic measures varied extensively across groups. The average resistance measure was highly correlated with peak flows in all subject groups and did not provide much additional information. McHenry et al. (1996) found that laryngeal resistance could vary widely within a speaker, and could reflect variation in flow, pressure, or in details of laryngeal setting. Because of this variability, they

questioned the utility of resistance measures for comparing across subjects and experimental conditions.

There is obviously a need for more extensive research into how measures of laryngeal function vary across speakers and speaker groups. The relative inaccessibility of the larynx puts a premium on data types that can be non-invasively obtained, such as acoustic and aerodynamic signals. But the utility of this data depends on adequate sources of normative data and on a clear understanding of how changes in laryngeal control parameters are reflected in the measurements taken from these signals, and work is needed on both of these fronts. Within populations controlled for age and gender, considerable cross-subject variation may exist in features as varied as the extent of voice source changes that occur with oral constriction (Bickley & Stevens 1986) and effects of SPL on f_0 levels in school-age children (McAllister & Sundberg 1996). The widely used open quotient measure is not fully understood as it relates to vibratory characteristics and voice quality types; for example, breathy voice is said to be characterized both by high values of open quotient and a fast rate of spectral drop-off, but Hanson's (1997) subjects did not show strong correlations between these two variables. Finally, the current data indicate that interrelationships among variables may differ across speaker groups. This general observation has been made in acoustic studies as well. McAllister and Sundberg (1996) found age differences in how SPL variation affects f_0 , and Fant and Lin (1988) obtained a gender-by-vowel interaction for SPL effects on f_0 in adults. Nittrouer et al. (1990) correlated acoustic measures of voice quality (e.g., spectral tilt, jitter, signal-to-noise ratios) and found that relationships between jitter and spectral tilt differed between men and women.

These examples suggest that we are only beginning to describe the range of variation in laryngeal behavior and voice source measures, and that some measures of vocal function may be sensitive to physical differences in the speech production system. In the case of the VOT_h data, the existence of group patterns implies systematic differences in the balance of forces involved in voicing control. Differences in laryngeal structure and aerodynamic quantities presumably account for some of these differences.

4.5 Discussion of Sections 3.5: Characteristics of voiced and voiceless tokens within individuals (microscopic analysis)

Discussion of Sections 3.5.1-2

Analysis of individual tokens was undertaken as another way of investigating group effects on the determinants of voicing onsets. With VOT_h duration as the dependent variable, the correlates of VOT_h were compared across speakers. Results derived from these analyses were often similar to those obtained for the averaged data, but not always: For example, in section 3.4 there was a weak tendency for women with higher f_0 's to show more voiced /h/, but within individual women (as for men and children), the tokens with voicing breaks were more likely to have high f_0 's relative to the speaker's own range.

For all speakers, some number of significant relationships occurred among the measured variables, but there was extensive variation in the consistency of the effects and in the parameters involved. This variation was unrelated to the prevalence of /h/ voicing across speakers. Nevertheless, a few group

tendencies could still be discerned, particularly involving AC flow measure. In the children, AC flow almost always (6 of 7 cases) correlated negatively with VOT_h. This was observed in some of the men as well, but more commonly the men demonstrated positive correlations between AC flow and f_0 . Half the women showed a positive correlation between AC flow and VOT_h (i.e., the opposite of what was seen in the 5-year-olds), but the clearest pattern among the women was a positive relationship between AC flow and peak flow. From this summary it is clear that vibrational amplitudes are subject to rather different influences in our three speaker groups.

Some of the most interesting individual differences involved pressure effects on f_0 and AC flow. In several subjects, AC flow bore a positive relation to pressure, following the expectation that vibratory amplitudes will be larger under increased driving pressures. In nearly all subjects, AC flow decreased in the vicinity of the /h/ flow peak. In nearly all adults, f_0 decreased as well. In the 5-year-olds, however, lowered f_0 around /h/ was both less common and less extensive. One issue that arises in interpreting these data is that the f_0 and AC flow measures were necessarily made at various times during the adduction phase, depending on the duration of any voicing break.

Previous studies disagree on the patterns of f_0 variation around /h/. Modeling studies and some data sets show a pattern of increased f_0 (Bickley 1991; Manuel & Stevens 1989), but it is also well-known that subglottal pressure may show a momentary dip in the vicinity of a major abduction (Löfqvist 1975; Ohala & Ohala 1972; Ohala 1990; Slis & Damsté 1967), which ought to lower vibrational frequency. In the current data, the pressure effect appears to win out, at least among adults. It may be that in a child's larynx the

decrease in airway resistance during abduction is not sufficient to bring on a substantial pressure change, leading to less of a pressure effect on f_0 . Another possibility is that vocal fold tension undergoes greater increase around abduction in children than adults. This could mean either that children actively increase tension during a devoicing maneuver more than adults, or else that children experience relatively more tension increase than adults because of physical differences in the vocal folds themselves. Development of the vocal ligament and changes in vocal-fold tissue structure are relevant factors to consider here.

There has been considerable discussion in the literature about whether speakers use active tension increase as a means of suppressing voicing in voiceless consonants, particularly by contracting the cricothyroid (CT) muscle (e.g., Dixit & MacNeilage 1980; Hirose & Ushijima 1978; Hirose et al. 1978; Kagaya & Hirose 1975; Löfqvist et al. 1989; Sawashima & Hirose 1983). There appears to be some interspeaker variation in the extent to which this strategy may be used, and there may be cross-language effects as well (cf. Löfqvist et al. 1989; MacNeilage 1974; Sawashima & Hirose 1983). There are suggestions in the current data that differential use of CT activity across speakers may contribute to the cross-subject variation in percentage of voiced /h/. For example, the one adult speaker (AF7-LK) with a higher f_0 in the vicinity of /h/ also was one of the two women whose /h/'s were always devoiced. A speaker's habitual level of CT activity may also be a factor. One of the two men with a higher percentages of voiced /h/, AM1-RM, used a somewhat high f_0 (140–150 Hz) during his stressed vowel compared to the other men. These two examples indicate that amid certain group tendencies, speakers nevertheless have some latitude for adopting individual phonatory control

strategies, and that some effects of these strategies may be evident in the speaker's consonantal voicing patterns.

Discussion of Section 3.5.3

In this section, individual /h/ productions were studied in several speakers as part of an attempt to determine how completely the measured variables could account for speakers' /h/ voicing patterns. Since the number of tokens available for these analyses varied widely across speakers, this question was approached in an observational fashion, working from scatter plots and percentile rankings across tokens of the measured variables. The results suggest that more sophisticated multidimensional analysis would be a fruitful approach to data of this sort. A future study using such techniques will need to take a very specific focus in order to collect more repetitions of /h/, possibly under different speaking conditions, than were available here.

In subjects whose /h/'s were usually voiced, the occasional devoiced /h/ frequently proved to be an outlier on one or more other dimensions. Across all subjects, voiceless tokens were characterized by high peak flows and low AC flows; pressure and f0 effects differed across subjects. In particular, devoicing in children tended to occur in the context of low f0 values, whereas in adults the opposite was usually observed. In subjects whose /h/'s were usually voiceless, the occasional voiced /h/ was usually characterized by low f0's and AC amplitudes, and sometimes by low /h/ flow peaks. Descriptions in terms of outlying values were most successful in subjects with a clear majority voicing type. Relationships among variables were similar in subjects with more balanced VOTH distributions, but the patterns were much less distinct.

Within a subject, the relationship between VOTH and the other measures was probabilistic. For example, a speaker who showed a strong relationship between flow peaks and devoiced /h/ might still show low AC flows in occasional tokens, and low AC flows might account for some tokens that failed to show the expected flow peak effect. In this way also, two subjects whose correlation matrices differed extensively might end up showing similar influences on their /h/ voicing, albeit to varying degrees. No single way of representing relationships among variables was sufficient for all the data. In some cases the correlation matrices were most revealing; elsewhere it might be the scatter plots or percentile rankings. It is clear that prediction of voicing behavior for multiple individuals ultimately requires simultaneous characterization of several aspects of their laryngeal and aerodynamic activity. This again suggests that future studies should be designed to allow for multidimensional statistical analysis.

In the five subjects with mostly voiced /h/, the 4 variables (Pkflow, AC flow, f_0 , pressure) were not sufficient to characterize every instance of devoiced /h/, but they did account for a substantial majority. Measures of pulse shape like those sometimes made in voice quality studies (cf. review in chapter 1) may account for some of the remaining cases. Since voicing depends on achieving balance among a number of physical factors, it is hardly surprising that our subset of measures does not account for every /h/ token. What is more striking is how much of the data we are able to account for using a modest set of easily measured variables in noninvasively obtained signals.

5. Summary and conclusions

The basic question underlying this study was whether speakers would show age and/or gender effects on consonantal voicing behavior in accord with known group differences in laryngeal and aerodynamic quantities. The simple answer to this question is that they do. To explore some of the implications of this finding, it is useful to summarize the results in terms of age and gender differences.

5.1 Age effects

The most salient and consistent effect of age was increased variability (as measured by standard deviation) among the children as compared to the adults. Higher average standard deviations for the child group were seen for all measures except the /h/ flow peaks, and the differences were significant for /p, t/ VOTs, VOTh, and vowel duration. Although statistical measures were not made of /h/ flow excursion shape, visual inspection suggests that the children were also more variable in the time course of ab/adduction.

The greater variability of VOTh in children implies that voicing control itself is immature at 5 years of age. The /h/ flow excursions suggest that control of the abduction maneuver constitutes at least some part of this. Thus, the protracted course of acquiring adultlike VOT values in aspirated stop VOTs probably owes to issues of laryngeal as well as interarticulator timing control. This conclusion receives further support from the fact that the same child subjects who produced the longest VOTs in /p, t/ also yielded the longest values of VOTh. These findings force us to reconsider the extent to which

VOT data may be used as evidence for improving articulatory timing skill. Insofar as VOT reflects laryngeal and aerodynamic factors, previous attempts at charting timing control development by means of VOT measures must be regarded with caution.

5.2 Gender or sex effects

The primary gender effect was a difference in voicing behavior for /h/. Women showed more devoiced /h/ and greater cross-subject variability in abduction degree than men. Some women yielded values comparable to men's while others showed patterns similar to the children's. The data strongly suggest that men are more likely than women to voice throughout a typical abduction gesture, and that, in general, men will show voicing over a wider range of laryngeal settings than women. Without further data it is not possible to pinpoint exactly which laryngeal and aerodynamic factors are most responsible for producing the observed differences in /h/ voicing, nor to determine the extent to which these differences arise from necessary, inherent conditions or from alterable settings. It is unlikely, however, that sociological factors play a major role in /h/ voicing behavior. More likely explanations involve the terms of the phonation threshold pressure equation. The voice quality literature has long suggested that differences in vocal-fold structure contribute to gender differences in some aspects of laryngeal function; the present data offer the additional, more provocative suggestion that gender effects may be observed for contrastive voicing as well.

5.3 Individual variation

Although group tendencies could be stated for /h/ voicing, individuals showed considerable variation of degree. This was especially true for the women. These differences may be partly attributable to how much individuals use longitudinal tension of the vocal folds to supplement abduction, either as a habitual (voice quality) setting or specifically as a devoicing strategy. This sort of cross-speaker variation may also account for past inconsistencies in reported f_0 variation around /h/.

More generally, measures of /h/ flow peaks, pressure, AC flow and f_0 did a fairly good job of accounting for /h/ voicing patterns within subjects. However, the correlational analyses suggested that subjects varied considerably in which factors were used most extensively and consistently. The fact that one adult showed two distinct patterns also supports the notion that individual speakers adopt unique strategies. The aerodynamic equations for voicing provide a preliminary definition of the ranges within which speakers can vary. Again, one of the more interesting implications is that such differences in strategy may have some effect on voicing control in distinctive as well as nondistinctive environments.

5.4 Lingering issues

The correlational analyses are useful mainly in suggesting directions for future work. Although correlations cannot establish causality, the data suggest that voicing behavior is differentially sensitive to some parameters across speaker groups. In men, but not women, pulse amplitude showed a

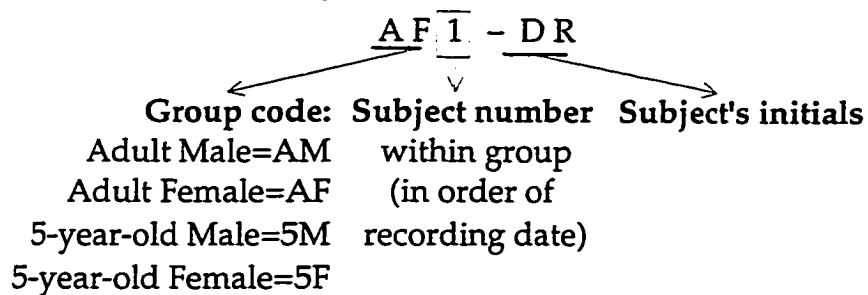
negative relationship with f_0 , suggesting that longitudinal tension may have had a significant effect on vibrational amplitudes for some of our adult males. Among women, /h/ peak flow levels were more closely related to pulse amplitude. This could be a general effect of larynx size. Multidimensional statistics, including measures of glottal pulse shape and other source characteristics, should shed further light on how different speakers manipulate laryngeal and aerodynamic variables to achieve voicing states. Such analyses may not entirely supplant the simple observational methods used here, however, since any typical body of data will contain a few outliers. Only through a combination of analyses can one observe similar patterns in results differing in statistical power.

5.5 Conclusions

Theoretical descriptions of vocal-fold vibration indicate that a number of parameters can be manipulated to achieve phonation. Consequently, predication of voicing behavior across and within individuals ultimately requires simultaneous characterization of several laryngeal and aerodynamic variables. Results of such analyses will offer greater insight into the developmental VOT literature and will also help bridge the gap between the voice quality literature, which has concentrated mostly on noncontrastive aspects of speech, and the more traditional phonetic studies into the laryngeal means of effecting linguistic distinctions. The group differences in /h/ voicing indicate that valid interpretation of voicing data, including VOT results, requires a thorough understanding of the aerodynamics of voicing thresholds and the kinematics of laryngeal abduction in different populations. The cross-group and cross-subject differences in voicing

behavior observed here are a general caveat to researchers studying aspects of voice across speaker populations. They underscore the need for collecting a wider range of voice source data from male and female speakers of all ages and point to a need for more extensive research into how various laryngeal parameters may vary across speakers and speaker groups.

Subject identification codes:



<u>Adult males</u>	<u>age</u>	<u>Adult females</u>	<u>age</u>	<u>5 year olds</u>	<u>age</u>
subj. id	(yrs)	subj. id	(yrs)	subj. id	(yrs)
*AM1-RM	41.9	AF1-DR	42.9	5F1-HJ	5.3
AM2-JG	28.6	AF2-MS	44.3	5F2-EC	5.2
AM3-DH	33.3	AF3-PC	27.1	5F3-HH	4.7
AM4-SL	30.4	AF4-DB	27.7	5M1-DJ	5.3
AM5-LR	57.7	AF5-MD	51.3	5M2-SS	5.7
AM6-ED	29.2	AF6-MP	38.7	*5M3-LEZ	5.9
AM7-BG	26.6	*AF7-LK	30.4	5M4-MM	5.8
avg. =	35.4	avg. =	37.5	avg. =	5.4

*Pressure data are unavailable for these subjects

Table 2.1: Subject ages and identification codes

Additional information on child subjects summarized from forms filled out by parents at time of testing

Subj	Geographical variation	Notable language history or influences	Medical history
DJ	None.	Learned a few words of Yiddish through maternal grandparents; knew some numbers in Spanish.	Tonsils & adenoids removed 6 weeks prior to recording. Older sister had moderate hearing loss in 1 ear.
SS	None.	Nothing noteworthy.	Occasional heavy ear wax.
HJ	None.	Nothing noteworthy.	No significant history.
EC	None.	An "early talker" according to pediatrician (mother estimated first words at 10 months).	Tonsils removed; many ear infections as a young child but had decreased in frequency at time of recording.
HH	None.	Exposed to Mandarin at younger ages through father's friends. Started imitating speech at c. 1 month & didn't produce much babbling (either canonical or variegated)*	Mother mildly dyslexic.
LEZ	adopted out of Colombia, South America at 3 months.	Some exposure to Hebrew through synagogue; a few words of Spanish. Mother reported that he taught himself to read fluently at 4 years.	None since adoption; none known previous to that.
MM	Vermont until age 2.	Nothing noteworthy.	No significant history.

* HH's father was a graduate student in linguistics at Yale.

Table 2.2: Additional information on child subjects

Table 2.3a:
Summary data for SALT analyses of child language samples

Subj.	sex	age (mo)	N utts	N wds	TTR	MLU wrđ	MLU mrph	Brown* stage	Miller & Chapman* prediction
DJ	M	63	48	212	0.40	4.61	5.17	postV	w/in 60mo rg
SS	M	68	47	250	0.39	5.56	6.13	postV	w/in 60mo rg
HJ	F	62	36	323	0.20	8.97	9.92	postV	+60mo rg
EC	F	63	31	210	0.50	6.77	7.19	postV	+60mo rg
HH	F	56	40	348	0.29	8.70	10.32	postV	+60mo rg
LEZ	M	71	28	194	0.37	7.46	8.04	postV	+60mo rg
MM	M	69	35	234	0.45	6.88	7.29	postV	+60mo rg

*Brown (1973), Miller & Chapman (1981)

TTR = Type-token ratio

MLU = Mean length of utterance, in morphemes or in words. Mean length values here exclude interrupted and aborted utterances

Table 2.3b:
Utterance length distributions (in morphemes) for child language samples

utt length	1	2	3	4	5	6	7	8	9	10	11	12	13	Sum
DJ	5	10	11	4	0	5	1	2	2	0	1	2	3	46
SS	1	0	2	5	12	8	8	1	6	1	0	0	1	45
HJ	0	1	4	0	0	2	3	2	5	7	3	2	7	36
EC	5	1	3	2	2	2	1	4	2	4	0	0	5	31
HH	1	1	0	1	5	2	3	3	0	1	5	5	13	40
LEZ	0	1	1	1	1	6	4	3	3	1	0	2	3	26
MM	7	1	1	5	2	1	3	2	0	1	2	2	7	34

Tables 2.3a–b: Summaries of language sample data for child subjects

Statistical analysis on original and remeasured values
 Showing mean (μ) and maximum differences (∂)
 between two measurement sets
 and results of correlational analysis

Variable	N	$\mu\partial$	max $ \partial $	r-value	p-value
VOT (msec)	145	1.812	18.985	.985	<.0001
<u>each stop measured separately:</u>					
VOT-b	21	1.359	6.265	.898	<.0001
VOT-d	21	.442	18.985	.595	.0036
VOT-p	62	1.972	14.011	.986	<.0001
VOT-t	41	2.504	14.184	.956	<.0001
VOT _h (msec)	42	-.571	26.200	.958	<.0001
Pres (cmH ₂ O)	73	.013	.192	1.000	<.0001
Pkflow (l/m)	42	-.181	3.512	.999	<.0001
Vdur1 (msec)	53	1.418	34.032	.990	<.0001
Vdur2 (msec)	59	1.977	63.900	.979	<.0001

Table 2.4: Summary of measurement reliability analysis

/b/ VOT (msec)	RM	JG	DH	SL	LR	ED	BG
N	59	34	24	15	24	20	16
Mean	14.830	12.206	11.875	4.000	6.667	9.000	13.125
Max	25	20	20	20	10	15	25
Min	10	5	5	0	0	0	0
Median	15	10	15	5	5	10	15
Skew	0.800	0.220	-0.380	1.630	-0.050	-0.050	-0.260
Skew/SE	2.490	0.515	-0.757	2.574	-0.103	-0.092	-0.432
SE	0.420	0.525	0.893	1.397	0.576	1.000	1.573
StDev	3.210	3.063	4.377	5.412	2.823	4.472	6.292
Variance	10.320	9.381	19.158	29.286	7.971	20.000	39.583
Mode	15	10	15	0	5	n.u.	15
Range	15	15	15	20	10	15	25
Q3-Q1/2	0.000	2.500	2.500	2.500	2.500	4.375	2.500
WStat	0.730	0.783	0.822	0.714	0.728	0.869	0.934
SigLevel	<.001	<.001	0.001	<.001	<.001	0.011	0.278

/p/ VOT (msec)	RM	JG	DH	SL	LR	ED	BG
N	53	71	60	58	83	48	40
Mean	56.700	41.831	46.917	34.310	44.277	38.021	36.375
Max	95	80	85	55	70	50	50
Min	30	15	20	20	20	20	20
Median	55	40	45	35	45	40	35
Skew	0.380	0.250	0.390	0.390	-0.050	-0.020	-0.270
Skew/SE	1.120	0.864	1.235	1.226	-0.184	-0.050	-0.699
SE	2.070	1.670	1.883	0.916	1.266	0.985	1.132
StDev	15.090	14.072	14.587	6.974	11.533	6.821	7.160
Variance	227.830	198.028	212.790	48.639	133.008	46.531	51.266
Mode	n.u.	45	50	30	40	40	40
Range	65	65	65	35	50	30	30
Q3-Q1/2	11.250	12.500	11.875	5.000	10.000	4.375	4.375
WStat	0.960	0.965	0.965	0.933	0.959	0.929	0.938
SigLevel	0.180	0.129	0.180	0.004	0.035	0.007	0.040

n.u. = not unique

Tables 3.1a: VOT distributional statistics for /b p/: Men

/b/ VOT (msec)	DR	MS	PC	DB	MD	MP	LK
N	36	12	23	22	20	19	27
Mean	10.833	12.917	21.522	20.227	9.250	3.421	9.259
Max	15	20	35	35	20	10	20
Min	5	0	10	15	0	0	0
Median	10	15	20	20	10	5	10
Skew	0.280	-0.780	0.370	1.510	-0.270	0.100	-0.130
Skew/SE	0.696	-1.110	0.726	2.884	-0.500	0.181	-0.271
SE	0.423	1.564	1.235	1.013	1.463	0.668	0.988
StDev	2.536	5.418	5.923	4.750	6.540	2.912	5.133
Variance	6.429	29.356	35.079	22.565	42.829	8.480	26.353
Mode	10	15	20	20	15	5	10
Range	10	20	25	20	20	10	20
Q3-Q1/2	0.000	2.500	2.500	0.625	6.875	2.500	0.000
WStat	0.677	0.862	0.923	0.717	0.862	0.745	0.806
SigLevel	<.001	0.049	0.078	<.001	0.008	<.001	<0.001

/p/ VOT (msec)	DR	MS	PC	DB	MD	MP	LK
N	36	36	55	72	49	57	79
Mean	43.611	48.472	44.545	47.153	36.633	36.228	79.747
Max	70	70	70	85	65	65	125
Min	25	20	20	25	15	10	55
Median	42.5	50	45	45	35	35	80
Skew	0.450	-0.360	0.030	0.390	0.430	0.170	0.420
Skew/SE	1.091	-0.887	0.078	1.353	1.237	0.537	1.510
SE	1.811	1.813	1.526	1.654	1.323	1.565	1.744
StDev	10.864	10.877	11.315	14.038	9.264	11.813	15.502
Variance	118.016	118.313	128.030	197.061	85.821	139.536	240.320
Mode	n.u.	n.u.	50	35	40	40	80
Range	45	50	50	60	50	55	70
Q3-Q1/2	7.500	5.000	7.500	10.000	5.000	10.000	10.000
WStat	0.941	0.954	0.965	0.950	0.960	0.973	0.958
SigLevel	0.073	0.190	0.210	0.016	0.164	0.432	0.035

n.u. = not unique

Tables 3.1b: VOT distributional statistics for /b p/: Women

/b/ VOT (msec)	DJ	SS	HJ	EC	HH	LEZ	MM
N	12	10	12	5	13	12	12
Mean	21.667	15.000	16.250	7.000	8.846	11.667	7.500
Max	45	20	25	15	20	20	15
Min	0	10	10	0	0	0	0
Median	23	15	15	5	10	15	5
Skew	-0.020	0.000	0.400	0.190	0.700	-0.850	0.340
Skew/SE	-0.022	0.000	0.564	0.177	1.033	-1.208	0.478
SE	3.710	0.745	1.523	2.550	1.617	1.777	1.306
StDev	12.851	2.357	5.276	5.701	5.829	6.155	4.523
Variance	165.152	5.556	27.841	32.500	33.974	37.879	20.455
Mode	n.u.	15	15	5	n.u.	15	5
Range	45	10	15	15	20	20	15
Q3-Q1/2	19.375	0.000	14.375	15.000	12.500	2.500	2.500
WStat	0.985	0.648	0.875	0.961	0.846	0.809	0.867
SigLevel	0.986	<.001	0.072	0.813	0.024	0.010	0.057

/p/ VOT (msec)	DJ	SS	HJ	EC	HH	LEZ	MM
N	55	36	27	18	30	20	30
Mean	104.000	38.750	58.889	55.278	48.000	27.000	36.333
Max	185	105	110	85	125	60	85
Min	40	15	20	25	5	15	10
Median	105	35	50	55	45	25	35
Skew	0.280	0.950	0.460	0.360	0.740	1.110	0.700
Skew/SE	0.846	2.338	0.976	0.624	1.662	2.026	1.559
SE	3.322	3.648	5.517	3.488	5.032	26.010	3.162
StDev	24.634	21.889	28.667	14.800	27.562	11.630	17.317
Variance	606.852	479.107	821.795	219.036	759.655	135.263	299.885
Mode	100	n.u.	40	55	n.u.	20	35
Range	145	90	90	60	120	45	75
Q3-Q1/2	12.500	15.000	22.500	18.125	13.750	7.500	15.000
WStat	0.963	0.899	0.905	0.934	0.929	0.862	0.944
SigLevel	0.170	0.003	0.018	0.230	0.055	0.008	0.138

n.u. = not unique

Tables 3.1c: VOT distributional statistics for /b p/: 5-year-olds

/d/ VOT (msec)	RM	JG	DH	SL	LR	ED	BG
N	12	24	12	15	24	9	16
Mean	14.580	10.625	12.917	11.667	6.250	14.444	12.500
Max	20	15	15	25	15	20	20
Min	0	0	5	5	0	5	5
Median	17.5	15	15	5	5	20	15
Skew	-1.050	-0.860	-1.250	0.620	0.560	-0.350	-0.620
Skew/SE	-1.480	-1.720	-1.769	0.979	1.126	-0.430	-1.019
SE	2.170	1.422	1.145	2.218	0.915	2.274	1.208
StDev	7.530	6.965	3.965	8.591	4.484	6.821	4.830
Variance	56.630	48.505	15.720	73.810	20.109	46.528	23.333
Mode	20	15	15	5	5	20	15
Range	20	15	10	20	15	15	15
Q3-Q1/2	4.380	7.500	1.875	7.500	2.500	6.250	4.375
WStat	0.730	0.573	0.576	0.730	0.835	0.747	0.737
SigLevel	<.001	<.001	<.001	<.001	0.001	0.006	<.001

/t/ VOT (msec)	RM	JG	DH	SL	LR	ED	BG
N	13	48	36	30	48	40	32
Mean	66.540	43.438	62.222	43.833	53.333	43.500	35.938
Max	90	65	85	65	75	70	50
Min	55	20	50	25	20	25	5
Median	65	45	60	45	55	40	35
Skew	0.620	-0.310	0.910	-0.030	-0.510	0.420	-0.700
Skew/SE	0.920	-0.874	2.221	-0.063	-1.447	1.073	-1.627
SE	2.910	1.527	1.636	1.371	1.446	1.613	1.857
StDev	10.490	10.577	9.816	7.507	10.018	10.203	10.506
Variance	109.940	111.868	96.349	56.351	100.355	104.103	110.383
Mode	n.u.	40	55	45	55	40	n.u.
Range	35	45	35	40	55	45	45
Q3-Q1/2	8.750	5.000	5.000	2.500	6.250	5.000	7.500
WStat	0.900	0.946	0.872	0.833	0.944	0.954	0.928
SigLevel	0.130	0.045	<.001	<.001	0.036	0.144	0.040

n.u. = not unique

Tables 3.2a: VOT distributional statistics for /d t/: Men

/d/ VOT (msec)	DR	MS	PC	DB	MD	MP	LK
N	13	12	24	12	10	28	15
Mean	13.846	13.333	17.917	18.750	11.500	19.464	8.000
Max	15	15	30	25	20	35	15
Min	5	10	10	10	0	0	0
Median	15	15	15	20	12.5	20	10
Skew	-2.100	-0.620	0.840	-0.660	-0.180	-0.270	-0.240
Skew/SE	-3.084	-0.878	1.682	-0.934	-0.229	-0.573	-0.387
SE	0.831	0.711	1.082	1.393	2.693	1.345	1.363
StDev	2.996	2.462	5.299	4.827	8.515	7.115	5.278
Variance	8.974	6.061	28.080	23.295	72.500	50.628	27.857
Mode	15	15	15	20	20	n.u.	10
Range	10	5	20	15	20	35	15
Q3-Q1/2	0.000	2.500	2.500	1.875	8.125	5.000	2.500
WStat	0.454	0.613	0.842	0.806	0.839	0.945	0.878
SigLevel	<.001	<.001	0.001	0.009	0.042	0.170	0.044

/t/ VOT (msec)	DR	MS	PC	DB	MD	MP	LK
N	24	24	41	36	10	32	29
Mean	47.292	64.792	51.341	68.333	65.000	68.750	66.030
Max	65	80	80	95	80	100	95
Min	35	55	25	50	50	45	45
Median	47.5	65	50	65	67.5	67.5	65
Skew	0.200	0.520	0.070	0.450	-0.220	0.620	0.530
Skew/SE	0.396	1.045	0.178	1.106	-0.290	1.430	1.155
SE	1.620	1.519	1.905	2.200	3.162	2.330	2.022
StDev	7.937	7.442	12.198	13.202	10.000	13.198	10.888
Variance	62.998	55.389	148.780	174.286	100.000	174.194	118.534
Mode	50	65	55	65	70	60	60
Range	30	25	55	45	30	55	50
Q3-Q1/2	6.875	5.000	10.000	11.250	6.875	7.500	6.250
WStat	0.952	0.912	0.979	0.931	0.937	0.942	0.954
SigLevel	0.305	0.039	0.746	0.033	0.506	0.103	0.256

n.u. = not unique

Tables 3.2b: VOT distributional statistics for /d t/: Women

/d/ VOT (msec)	DJ	SS	HJ	EC	HH	LEZ	MM
N	10	11	12	7	11	8	15
Mean	8.000	12.273	16.250	17.143	12.727	10.625	6.667
Max	15	20	25	25	25	20	10
Min	0	5	10	10	0	0	0
Median	7.5	15	15	15	15	12.5	10
Skew	-0.030	-0.040	0.100	0.440	-0.090	-0.430	-0.600
Skew/SE	-0.038	-0.048	0.147	0.480	-0.117	-0.494	-0.947
SE	1.856	1.950	1.393	2.143	2.063	2.577	1.054
StDev	5.869	6.467	4.827	5.669	6.842	7.289	4.082
Variance	34.444	41.818	23.295	32.143	46.818	53.125	16.667
Mode	n.u.	5	n.u.	15	15	15	10
Range	15	15	15	15	25	20	10
Q3-Q1/2	15.625	7.500	14.375	15.000	12.500	16.250	2.500
WStat	0.883	0.829	0.897	0.794	0.955	0.872	-0.752
SigLevel	0.136	0.024	0.138	0.035	0.688	0.162	<.001

/t/ VOT (msec)	DJ	SS	HJ	EC	HH	LEZ	MM
N	20	22	24	21	22	22	25
Mean	107.750	54.545	60.208	47.381	52.727	38.864	46.000
Max	175	100	115	70	80	90	115
Min	45	20	20	25	20	5	15
Median	105	47.5	57.5	45	52.5	40	40
Skew	0.030	0.330	0.600	0.030	0.010	0.420	1.160
Skew/SE	0.059	0.640	1.196	0.048	0.028	0.803	2.369
SE	7.195	4.912	4.829	2.858	3.383	4.698	4.555
StDev	32.179	23.038	23.659	13.098	15.866	22.035	22.776
Variance	1035.461	530.736	559.737	171.548	251.732	485.552	518.750
Mode	105	40	60	45	40	40	40
Range	130	80	95	45	60	85	100
Q3-Q1/2	22.500	18.125	15.000	10.000	12.500	9.375	11.250
WStat	0.974	0.943	0.946	0.959	0.958	0.943	0.896
SigLevel	0.827	0.231	0.233	0.484	0.439	0.221	0.014

n.u. = not unique

Tables 3.2c: VOT distributional statistics for /d t/: 5-year-olds

Vdur1 (msec)	RM	JG	DH	SL	LR	ED	BG
N	50	58	60	58	83	47	40
Mean	192.800	88.865	88.551	90.746	111.713	107.555	91.611
Max	261.150	141.332	119.702	117.969	146.187	149.616	115.818
Min	118.470	60.992	53.741	63.683	81.528	53.035	71.010
Median	192.380	85.754	90.543	89.790	110.902	105.848	90.834
Skew	0.010	0.530	-0.240	0.100	0.420	-0.210	0.030
Skew/SE	0.040	1.644	-0.753	0.309	1.574	-0.590	0.076
SE	5.360	2.418	1.861	1.876	1.360	2.765	1.698
StDev	37.890	18.415	14.412	14.285	12.390	18.955	10.737
Variance	1435.290	339.102	207.699	204.074	153.520	359.305	115.293
Range	142.680	80.339	65.961	54.286	64.658	96.581	44.809
Q3-Q1/2	30.170	15.190	10.095	10.361	6.893	12.849	6.838

Vdur2 (msec)	RM	JG	DH	SL	LR	ED	BG
N	50	58	60	58	83	47	40
Mean	223.700	187.547	161.722	169.071	184.762	146.517	142.227
Max	278.800	222.400	201.800	212.800	206.800	177.699	195.200
Min	176.900	149.024	135.800	140.800	159.800	113.200	118.899
Median	226.400	189.650	161.850	168.950	185.500	148.600	138.800
Skew	0.040	-0.180	0.610	0.750	-0.120	0.000	0.920
Skew/SE	0.120	-0.558	1.923	2.340	-0.436	-0.009	2.386
SE	3.150	1.730	1.932	1.466	1.154	2.140	2.700
StDev	22.270	13.176	14.966	11.166	10.512	14.674	17.075
Variance	496.000	173.611	223.990	124.678	110.502	215.330	291.565
Range	101.900	73.376	66.000	72.000	47.000	64.499	76.301
Q3-Q1/2	14.940	6.682	10.713	6.575	8.600	9.600	11.350

Vdur1 refers to the unstressed vowel in the first syllable of the test utterance

Vdur2 refers to the stressed vowel of the utterance

Table 3.3a: Distributional statistics for
vowel duration measures: Men

Vdur1 (msec)	DR	MS	PC	DB	MD	MP	LK
N	60	60	59	62	48	57	74
Mean	102.345	106.778	103.738	85.541	104.646	116.093	103.090
Max	148.537	126.888	126.697	116.463	137.102	171.632	161.590
Min	57.117	85.470	81.858	60.561	82.232	74.219	70.657
Median	102.078	107.625	104.285	84.312	103.548	118.157	101.057
Skew	-0.010	-0.190	0.020	0.120	0.290	0.210	0.590
Skew/SE	-0.029	-0.585	0.058	0.373	0.815	0.649	2.081
SE	2.119	1.307	1.270	1.488	1.856	3.037	1.784
StDev	16.415	10.127	9.758	11.713	12.991	22.927	15.342
Variance	269.464	102.557	95.216	137.204	168.762	525.659	235.387
Range	91.419	41.418	44.839	55.903	54.870	97.413	90.933
Q3-Q1/2	10.040	6.219	6.072	8.755	9.919	16.852	9.276

Vdur2 (msec)	DR	MS	PC	DB	MD	MP	LK
N	60	60	59	62	48	57	74
Mean	146.318	195.715	180.488	165.723	170.882	172.876	203.869
Max	186.000	220.100	206.900	190.500	202.900	233.200	244.800
Min	112.000	168.700	156.800	132.000	151.900	110.699	172.000
Median	142.950	197.650	178.900	164.550	171.800	173.600	203.550
Skew	0.300	-0.160	0.080	-0.010	0.250	-0.110	0.350
Skew/SE	0.956	-0.517	0.265	-0.030	0.702	-0.330	1.224
SE	2.456	1.483	1.562	1.492	1.667	3.482	2.011
StDev	19.026	11.487	12.000	11.749	11.672	26.288	17.299
Variance	361.980	131.962	144.008	138.027	136.238	691.078	299.256
Range	74.000	51.400	50.100	58.500	51.000	122.501	72.800
Q3-Q1/2	13.100	8.688	8.500	7.213	9.350	21.775	11.500

Vdur1 refers to the unstressed vowel in the first syllable of the test utterance

Vdur2 refers to the stressed vowel of the utterance

Table 3.3b: Distributional statistics for
vowel duration measures: Women

Vdur1 (msec)	DJ	SS	HJ	EC	HH	LEZ	MM
N	54	34	27	0	0	19	0
Mean	342.959	218.467	121.118			164.743	
Max	504.635	296.493	168.855			272.632	
Min	227.533	136.146	62.265			112.232	
Median	343.001	228.454	120.559			145.243	
Skew	0.360	-0.200	-0.390			0.880	
Skew/SE	1.090	-0.469	-0.828			1.574	
SE	8.453	7.738	5.149			10.573	
StDev	62.114	45.119	26.756			46.085	
Variance	3858.142	2035.762	715.905			2123.783	
Range	277.102	160.347	106.590			160.400	
Q3-Q1/2	37.304	39.988	21.798			30.431	

Vdur2 (msec)	DJ	SS	HJ	EC	HH	LEZ	MM
N	54	34	27	18	34	19	0
Mean	383.793	215.802	204.685	149.500	126.859	217.032	
Max	644.900	315.900	276.700	202.400	166.900	330.800	
Min	254.800	130.700	158.000	117.200	98.600	123.300	
Median	378.753	203.300	196.400	144.350	124.550	211.500	
Skew	0.950	0.430	0.640	0.610	0.460	0.070	
Skew/SE	2.853	1.024	1.362	1.064	1.088	0.119	
SE	9.916	8.605	5.382	5.183	3.102	13.772	
StDev	72.865	50.173	27.968	21.992	18.087	60.031	
Variance	5309.305	2517.343	782.213	483.646	327.146	3603.773	
Range	390.100	185.200	118.700	85.200	68.300	207.500	
Q3-Q1/2	44.064	32.575	17.250	16.538	13.087	52.150	

Vdur1 refers to the unstressed vowel in the first syllable of the test utterance

Vdur2 refers to the stressed vowel of the utterance

Table 3.3c: Distributional statistics for
vowel duration measures: 5-year-olds

Tables 3.4: Average means, medians, and standard deviations of VOT and vowel duration measures within groups

Averages represent 7 subjects in each group except in the case of vowel duration, where N=4 for unstressed and N=6 for stressed in the 5-year-olds

Table 3.4a: Average mean values

	/b/	/d/	/p/	/t/	Vdur1 (unstr)	Vdur2 (str)
Men	10.2	11.9	42.6	49.8	110.3	173.6
Women	12.5	14.7	48.1	61.6	103.2	176.6
5-year-olds	12.6	12.0	52.6	58.2	211.8	216.3

Table 3.4b: Average median values

	/b/	/d/	/p/	/t/	Vdur1 (unstr)	Vdur2 (str)
Men	10.7	13.2	42.1	49.3	109.4	174.3
Women	12.9	15.4	47.5	61.1	103.0	176.1
5-year-olds	12.5	12.9	50.0	55.4	209.3	209.8

Table 3.4c: Average standard deviations

	/b/	/d/	/p/	/t/	Vdur1 (unstr)	Vdur2 (str)
Men	4.2	6.2	10.9	9.9	18.2	14.8
Women	4.7	5.2	12.0	10.7	14.2	15.6
5-year-olds	6.1	5.9	20.9	21.8	45.0	41.9

Tables 3.4: Average means, medians, and standard deviations of VOT and vowel duration measures within groups

Pkflow (l/m)	RM	JG	DH	SL	LR	ED	BG
N	48	33	48	30	48	40	32
Mean	63.125	50.303	44.792	35.000	33.021	48.500	32.969
Max	95	65	75	45	45	60	40
Min	40	40	20	25	20	40	25
Median	60	50	45	35	35	50	35
Skew	0.310	0.070	0.390	0.000	-0.380	-0.100	-0.130
Skew/SE	0.864	0.160	1.113	0.000	-1.074	-0.257	-0.293
SE	2.006	1.286	1.568	0.758	0.755	0.862	0.740
StDev	13.900	7.389	10.865	4.152	5.233	5.454	4.185
Variance	193.218	54.593	118.041	17.241	27.383	29.744	17.515
Mode	55	55	35	35	35	50	35
Range	55	25	55	20	25	20	15
Q3-Q1/2	11.875	5.000	9.375	1.250	2.500	4.375	2.500
WStat	0.935	0.905	0.964	0.882	0.910	0.895	0.869
SigLevel	0.015	0.008	0.233	0.003	0.001	0.001	0.001

Pres (cm H20)	RM	JG	DH	SL	LR	ED	BG
N	0	130	132	73	119	98	80
Mean		4.969	7.125	6.555	8.555	4.566	4.575
Max		7	12.5	7.5	10.5	5.5	6
Min		3.5	3	5	7.5	3.5	3
Median		5	7	6.5	8.5	4.5	4.5
Skew		0.170	0.930	-1.220	0.220	0.010	-0.510
Skew/SE		0.791	4.345	-4.250	0.963	0.032	-1.856
SE		0.058	0.150	0.060	0.050	0.040	0.070
StDev		0.667	1.726	0.511	0.544	0.397	0.627
Variance		0.445	2.979	0.261	0.296	0.158	0.393
Mode		5	6.5	6.5	8.5	4.5	5
Range		3.5	9.5	2.5	3	2	3
Q3-Q1/2		0.500	1.000	0.250	0.500	0.250	0.250
WStat		0.942	0.925	0.792	0.910	0.857	0.908
SigLevel		<.001	<.001	<.001	<.001	<.001	<.001

Table 3.5a: Distributional statistics for peak flow and pressure measurements: Men

Pkflow (l/m)	DR	MS	PC	DB	MD	MP	LK
N	36	24	44	48	40	48	53
Mean	68.333	64.375	15.341	11.771	31.750	3.125	46.792
Max	105	80	20	20	50	10	60
Min	40	45	5	5	15	0	35
Median	75	65	15	10	30	5	45
Skew	-0.060	-0.110	-0.390	0.570	0.090	0.370	-0.010
Skew/SE	-0.139	-0.222	-1.063	1.622	0.233	1.043	-0.017
SE	3.249	1.863	0.595	0.407	1.382	0.437	0.924
StDev	19.494	9.126	3.947	2.823	8.738	3.029	6.729
Variance	380.000	83.288	15.579	7.968	76.346	9.176	45.283
Mode	75	65	15	10	35	5	45
Range	65	35	15	15	35	10	25
Q3-Q1/2	16.875	6.875	2.500	2.500	6.875	2.500	2.500
WStat	0.914	0.962	0.832	0.731	0.959	0.738	0.922
SigLevel	0.009	0.484	<.001	<.001	0.213	<.001	0.002

Pres (cm H20)	DR	MS	PC	DB	MD	MP	LK
N	72	60	111	118	59	101	0
Mean	4.931	6.667	5.293	4.195	9.364	7.262	
Max	6.5	8	7	5	11	9.5	
Min	3.5	5.5	4.5	3.5	7.5	5	
Median	5	6.5	5.5	4	9.5	7.5	
Skew	-0.320	0.210	0.730	0.180	-0.320	-0.030	
Skew/SE	-1.098	0.666	3.130	0.819	-0.990	-0.133	
SE	0.091	0.076	0.036	0.034	0.098	0.098	
StDev	0.771	0.587	0.384	0.364	0.753	0.989	
Variance	0.594	0.345	0.148	0.133	0.568	0.978	
Mode	5.5	6.5	5.5	4	10	7	
Range	3	2.5	2.5	1.5	3.5	4.5	
Q3-Q1/2	0.688	0.500	0.250	0.250	0.500	0.750	
WStat	0.909	0.921	0.831	0.824	0.944	0.957	
SigLevel	<.001	0.001	<.001	<.001	0.015	0.011	

Table 3.5b: Distributional statistics for peak flow and pressure measurements: Women

Pkflow (l/m)	DJ	SS	HJ	EC	HH	LEZ	MM
N	38	22	30	12	42	23	41
Mean	12.237	30.909	5.833	8.333	25.119	23.696	23.537
Max	25	55	20	15	45	50	50
Min	5	0	0	5	5	5	0
Median	10	35	5	10	25	25	25
Skew	0.400	-0.450	0.890	0.340	0.080	0.570	0.220
Skew/SE	0.998	-0.856	1.996	0.474	0.201	1.121	0.587
SE	0.793	3.673	1.152	0.940	1.441	2.272	1.515
StDev	4.890	17.227	6.309	3.257	9.337	10.894	9.698
Variance	23.915	296.753	39.799	10.606	87.181	118.676	94.055
Mode	10	35	n.u.	10	30	25	n.u.
Range	20	55	20	10	40	45	50
Q3-Q1/2	12.500	15.625	15.000	12.500	5.625	17.500	7.500
WStat	0.894	0.911	0.808	0.786	0.962	0.955	0.963
SigLevel	0.001	0.047	<.001	0.005	0.261	0.368	0.292

Pres (cm H20)	DJ	SS	HJ	EC	HH	LEZ	MM
N	77	43	53	23	32	0	45
Mean	4.273	5.198	7.000	7.804	6.781		9.200
Max	8.5	8	9	10.5	9.5		12.5
Min	1.5	3	5	5	5		6.5
Median	4	5	7	7.5	6.75		9
Skew	0.500	0.340	0.050	-0.070	0.390		0.270
Skew/SE	1.775	0.898	0.143	-0.146	0.891		0.739
SE	0.171	0.182	0.115	0.289	0.189		0.256
StDev	1.501	1.196	0.838	1.388	1.070		1.720
Variance	2.254	1.430	0.702	1.926	1.144		2.959
Mode	4	4	6.5	7.5	6		n.u.
Range	7	5	4	5.5	4.5		6
Q3-Q1/2	11.000	1.000	10.500	11.000	10.750		1.250
WStat	0.958	0.947	0.965	0.984	0.960		0.938
SigLevel	0.043	0.067	0.225	0.953	0.327		0.026

n.u. = not unique

Table 3.5c: Distributional statistics for
peak flow and pressure measurements: 5-year-olds

<u>All tokens of /h/</u>							
VOT _h (msec)	RM	JG	DH	SL	LR	ED	BG
N	48	33	48	30	48	40	32
Mean	22.604	0	2.292	2.833	0	15.625	0
Max	85	0	30	45	0	70	0
Min	0	0	0	0	0	0	0
Median	0	0	0	0	0	0	0
Skew	0.770	0	3.040	3.320	0	1.030	0
Skew/SE	2.175	0	8.600	7.431	0	2.657	0
SE	4.391	0	1.124	1.972	0	3.581	0
StDev	30.422	0	7.784	10.803	0	22.651	0
Variance	925.521	0	60.594	116.695	0	513.061	0
Mode	0	0	0	0	0	0	0
Range	85	0	30	45	0	70	0
Q3-Q1/2	25.000	0	0.000	0.000	0	20.000	0
WStat	0.712	0	0.318	0.283	0	0.704	0
SigLevel	<.001	<.001	<.001	<.001	<.001	<.001	<.001

<u>Only tokens where VOT_h > 0</u>							
VOT _h (msec)	RM	JG	DH	SL	LR	ED	BG
N	19	0	4	2	0	15	0
Mean	57.105		27.500	42.500		41.667	
Max	85		30	45		70	
Min	25		20	40		20	
Median	60		30	42.5		40	
Skew	-0.290		-0.750	0.000		0.260	
Skew/SE	-0.511		-0.612	0.000		0.415	
SE	4.211		2.500	2.500		4.216	
StDev	18.357		5.000	3.536		16.330	
Variance	336.988		25.000	12.500		266.667	
Mode	n.u.		30	n.u.		40	
Range	60		10	5		50	
Q3-Q1/2	12.500		3.750	n.a.		12.500	
WStat	0.949		0.630	n.a.		0.904	
SigLevel	0.392		0.000	n.a.		0.112	

n.u. = not unique
n.a. = not applicable

Table 3.6a: Distributional statistics for VOT_h: Men

Table 3.6b: Women

<u>All tokens of /h/</u>							
VOT _h (msec)	DR	MS	PC	DB	MD	MP	LK
N	36	24	44	48	40	48	53
Mean	30.833	35.208	2.500	38.854	22.375	0	53.868
Max	65	45	50	75	60	0	95
Min	0	15	0	0	0	0	5
Median	30	40	0	45	25	0	50
Skew	-0.070	-0.900	3.720	-0.630	0.140	0	-0.340
Skew/SE	-0.170	-1.803	10.067	-1.781	0.359	0	-1.005
SE	3.697	1.519	1.459	3.074	1.977	0	1.712
StDev	22.184	7.442	9.675	21.294	12.506	0	12.467
Variance	492.143	55.389	93.605	453.446	156.394	0	155.425
Mode	0	40	0	45	30	0	50
Range	65	30	50	75	60	0	90
Q3-Q1/2	20.000	5.000	0.000	10.000	7.500	0	7.500
WStat	0.893	0.860	0.293	0.881	0.921	0	0.900
SigLevel	0.002	0.003	<.001	<.001	0.009	<.001	<.001

<u>Only tokens where VOT_h > 0</u>							
VOT _h (msec)	DR	MS	PC	DB	MD	MP	LK
N	27	23	4	40	35		53
Mean	41.111	29.348	27.500	46.625	25.571		53.868
Max	65	40	50	75	60		95
Min	20	15	0	15	5		5
Median	40	30	30	45	25		50
Skew	0.310	-0.110	-0.270	0.000	1.070		-0.340
Skew/SE	0.653	-0.216	-0.218	-0.008	2.575		-1.005
SE	2.879	1.189	10.308	2.091	1.650		1.712
StDev	14.957	5.702	20.616	13.223	9.760		12.467
Variance	223.718	32.510	425.000	174.856	95.252		155.425
Mode	30	30	30	45	30		50
Range	45	25	50	60	55		90
Q3-Q1/2	15.000	2.500	18.750	8.750	5.000		7.500
WStat	0.896	0.816	0.926	0.954	0.901		0.900
SigLevel	0.011	<.001	0.552	0.152	0.004		<.001

Table 3.6b: Distributional statistics for VOT_h: Women

Table 3.6c: 5-year-olds

<u>All tokens of /h/</u>							
VOTh (msec)	DJ	SS	HJ	EC	HH	LEZ	MM
N	38	22	30	*12	42	23	41
Mean	60.921	31.364	24.167	13.750	60.714	12.391	3.293
Max	135	120	85	50	155	115	90
Min	0	0	0	0	0	0	0
Median	72.5	0	0	0	65	0	0
Skew	-0.270	0.860	0.530	0.740	0.030	2.350	5.080
Skew/SE	-0.675	1.649	1.190	1.045	0.080	4.609	13.271
SE	7.752	8.592	5.425	6.003	6.267	5.905	2.301
StDev	47.787	40.302	29.714	20.794	40.614	28.319	14.731
Variance	2283.588	1624.242	882.902	432.386	1649.478	801.976	217.012
Mode	0	0	0	0	0	0	0
Range	135	120	85	50	155	115	90
Q3-Q1/2	52.500	30.625	30.000	18.750	27.500	2.500	0.000
WStat	0.823	0.777	0.743	0.674	0.926	0.520	0.254
SigLevel	<.001	<.001	<.001	<.001	0.011	<.001	<.001

<u>Only tokens where VOTh > 0</u>							
VOTh (msec)	DJ	SS	HJ	EC	HH	LEZ	MM
N	25	9	13	4	34	6	3
Mean	92.600	69.000	55.769	41.250	75.000	47.500	45.000
Max	135	120	85	50	155	115	90
Min	60	40	25	30	5	5	20
Median	95	60	60	42.5	70	45	25
Skew	-0.110	0.510	-0.150	-0.280	0.440	0.550	0.380
Skew/SE	-0.223	0.621	-0.226	-0.231	1.057	0.553	0.267
SE	4.312	10.621	4.154	4.270	5.273	15.956	22.546
StDev	21.560	31.863	14.979	8.539	30.748	39.083	39.051
Variance	464.833	1015.278	224.359	72.917	945.450	1527.500	1525.000
Mode	n.u.	40	60	n.u.	70	n.u.	n.u.
Range	75	80	60	20	150	110	70
Q3-Q1/2	18.750	31.250	8.750	8.125	13.750	30.625	35.000
WStat	0.943	0.857	0.949	0.972	0.959	0.929	0.803
SigLevel	0.185	0.087	0.548	0.823	0.283	0.581	0.122

n.u. = not unique

*Some of EC's /h/ flow peaks were slightly clipped, and as a result are not included in these analyses. It was clear, however, that all excluded tokens were fully voiced. Her /h/ voicing percents therefore overestimate the quantity of voiceless cases.

Table 3.6c: Distributional statistics for VOTh: 5-year-olds

Table 3.7a: Men

Subj. inits.	RM	JG	DH	SL	LR	ED	BG		
Total N	48	28	48	30	48	40	32		
N VOTH=0	29	28	44	28	48	25	32		
% VOTH=0	60%	100%	92%	93%	100%	63%	100%		
							Group		
							avg	max	min
							87%	100%	60%

Table 3.7b: Women

Subj. inits.	DR	MS	PC	DB	MD	MP	LK		
Total N	36	24	44	48	40	46	53		
N VOTH=0	9	0	41	8	5	46	0		
% VOTH=0	25%	0%	93%	17%	13%	100%	0%		
							Group		
							avg	max	min
							35%	100%	0%

Table 3.7c: 5-year-olds

Subj. inits.	DJ	SS	HJ	EC	HH	LEZ	MM		
Total N	38	22	26	12	42	23	41		
N VOTH=0	13	12	13	8	8	17	38		
% VOTH=0	34%	55%	50%	67%	19%	74%	93%		
							Group		
							avg	max	min
							56%	93%	19%

Tables 3.7: Numbers and percentages of fully voiced /h/ within subjects

Table 3.8a: Median values, all subjects

Medians	p VOT	t VOT	VOT _h	Pkflow	Pres	Vdur1	Vdur2
p VOT	1.0						
t VOT	0.776**	1.0					
VOT _h	0.639**	0.646**	1.0				
Pkflow	-0.097	-0.200	-0.011	1.0			
Pres	-0.311	-0.076	-0.266	-0.152	1.0		
Vdur1	0.608**	0.622**	0.381	-0.216	-0.303	1.0	
Vdur2	0.721**	0.766**	0.354	-0.173	-0.259	0.890**	1.0

Table 3.8b: Maximum values, all subjects

Maxima	p VOT	t VOT	VOT _h	Pkflow	Pres	Vdur1	Vdur2
p VOT	1.0						
t VOT	0.791**	1.0					
VOT _h	0.643**	0.546**	1.0				
Pkflow	-0.145	-0.305	0.027	1.0			
Pres	0.190	0.252	0.036	-0.037	1.0		
Vdur1	0.757**	0.822**	0.690**	-0.102	0.076	1.0	
Vdur2	0.717**	0.878**	0.462*	-0.175	0.055	0.958**	1.0

Table 3.8c: Standard deviations, all subjects

SDs	p VOT	t VOT	VOT _h	Pkflow	Pres	Vdur1	Vdur2
p VOT	1.0						
t VOT	0.718**	1.0					
VOT _h	0.639**	0.718**	1.0				
Pkflow	0.153	0.056	0.362~	1.0			
Pres	0.504*	0.545*	0.338	0.278	1.0		
Vdur1	0.606**	0.847**	0.817**	0.284	0.617*	1.0	
Vdur2	0.461*	0.885**	0.713**	0.208	0.584*	0.945**	1.0

Table 3.8d: Counts for each cell

Missing data points meant that cells differed in the number of cases represented

	p VOT	t VOT	VOT _h	Pkflow	Pres	Vdur1	Vdur2
p VOT	1.0						
t VOT	N=21	1.0					
VOT _h	N=21	N=21	1.0				
Pkflow	N=21	N=21	N=21	1.0			
Pres	N=18	N=18	N=18	N=18	1.0		
Vdur1	N=18	N=18	N=18	N=18	N=15	1.0	
Vdur2	N=20	N=20	N=20	N=20	N=17	N=18	1.0

Missing Vdur1 measures: 5F2-EC, 5F3-HH, 5M4-MM

Missing Vdur2 measures: 5M4-MM

Missing Pres measures: AM1-RM, AF7-IK, 5M3-LEZ

Vdur1 refers to the unstressed vowel in the first syllable of the test utterance

Vdur2 refers to the stressed vowel of the utterance

Table 3.8: Correlations across subjects for /p, t/ VOTs, VOT_h, aerodynamic and vowel duration measures

	Body size measures		F0 measures			Aerodynamic measures			
	% VOTh=0	height neck (cm)	min. f0 (Hz)	avg mid-V f0 (Hz)	avg onset f0 (Hz)	avg. peak flow (l/m)	avg. AC flow (l/m)	avg. Pres (cm H ₂ O)	avg. resis. (pres/ flow)
Adult males									
AM1-RM	60	172.1	119	155	137	63.1	6.0	5.0	.099
AM2-JG	100	189.5	106	84	81	50.3	4.8	7.1	.167
AM3-DH	92	173.0	106	109	109	42.5	4.4	6.6	.189
AM4-SL	93	181.0	93	103	97	35.0	4.3	8.6	.261
AM5-LR	100	175.3	82	112	87	33.0	4.0	4.6	.095
AM6-ED	63	171.5	99	118	113	48.5	3.9	4.6	.139
AM7-BG	100	184.8	102	127	117	33.0	4.9	4.9	
Adult females									
AF1-DR	25	160.0	130	220	203	68.3	5.1	4.9	.072
AF2-MS	0	164.5	159	214	209	64.4	6.0	6.7	.104
AF3-PC	93	164.1	173	205	196	15.3	2.1	5.3	.346
AF4-DB	17	169.2	190	205	220	11.8	1.2	4.2	.356
AF5-MD	13	173.7	152	183	177	31.8	2.2	9.4	.296
AF6-MP	100	162.6	153	155	147	3.1	5.0	7.3	2.355
AF7-IK	0	163.8	150	165	184	46.8	3.1		
5-year-olds									
5M1-DJ	34	118.7	233	269	278	12.2	0.9	4.3	.352
5M2-SS	55	124.5	159	204	209	30.9	3.2	5.2	.168
5F1-HJ	50	115.6	157	191	218	5.8	1.0	7.0	1.207
F52-BC	67	116.8	228	234	233	8.3	1.4	7.8	.940
5F3-HH	19	104.8	234	294	307	25.1	1.0	6.8	.271
5M3-LEZ	74	113.7	*311	294	290	23.7	4.3		
5M4-MM	93	108.0	207	273	295	23.5	6.7	9.2	.391

* We were not very successful in explaining the difference between loudness and pitch to this subject

Table 3.9: Subject values for VOTh, body size, f0 and aerodynamic measures

Tables 3.10a-b: Comparing how average measures correlate with VOTH and body size measures in the 3 speaker groups

Table 3.10a: Correlations with VOTH

	Men	Women	5-year-olds	Pooled
Ht	+6	-2	+0	+2
Neck	+5	-3	-3	+4
Min.f0	-5	+3	+1	-3
MidVf0.avg	-7	+3	-0	-4
Onsetf0.avg	-7	+0	-1	-4
Pkflow.avg	-8	-5	+1	-1
ACflow.avg	-3	-3	+8	+3
Pres.avg	+4	-3	+7	+1
Resis.avg	+4	-3	+7	-0

Table 3.10b: Correlations with body size measures

	Height			
	Men	Women	5-year-olds	Pooled
Neck	+3	+8	+8	+9
Min.f0	-1	+4	-4	-8
MidVf0.avg	-6	-4	-7	-8
Onsetf0.avg	-5	-3	-8	-9
Pkflow.avg	-3	-5	-1	+6
ACflow.avg	+1	-6	-2	+4
Pres.avg	-4	+6	-6	-2
Resis.avg	-4	+6	-6	-6

				Neck			
				Men	Women	5-year-olds	Pooled
Neck				+1	-3	-5	-8
Min.f0				-2	-5	-7	-9
MidVf0.avg				-3	-7	-8	-9
Onsetf0.avg				-0	-1	-1	+5
Pkflow.avg				+3	-2	-5	+4
ACflow.avg				+5	+9	-6	+0
Pres.avg				+5	+9	-6	-5
Resis.avg							

Tables 3.10: Comparing how average measures correlate with each other in the 3 speaker groups

Tables 3.10c-d: Comparing how average measures correlate with f0 and aerodynamic measures in the 3 speaker groups

Table 3.10c: Correlations with f0 measures

	Min f0			MidV f0			Onset f0		
	Men	Women	5-year-olds	Men	Women	5-year-olds	Men	Women	5-year-olds
MidVf0.avg	+5	+0	+8	+9	+9	+9	+98	+98	+98
Onsetf0.avg	+7	+5	+7	+9	+9	+9	-4	-4	-4
Pkflow.avg	+8	-8	+1	-5	+2	+4	-3	+3	+3
ACflow.avg	+8	-6	+2	-4	+4	+3	+1	+1	+1
Pres.avg	-7	-3	+1	+1	-7	+1	+1	-8	+2
Resis.avg	-8	+8	-3	+4	-6	-6	+3	-1	-4

Table 3.10d: Correlations with aerodynamic measures

	Pkflow			ACflow			Pres		
	Men	Women	5-year-olds	Men	Women	5-year-olds	Men	Women	5-year-olds
ACflow.avg	+7	+9	+5	+7	+7	+7	+1	+1	+1
Pres.avg	-5	-1	-1	-1	-5	+0	+6	-0	+3
Resis.avg	-8	-99	-9	-7	-4	-96	-3	-0	+3

Tables 3.10: Comparing how measured variables correlate with each other in the 3 speaker groups

Correlations performed with all tokens of /h/				Correlations performed only with tokens where VOTH>0								
Men		Women		5-year-olds		Men		Women		5-year-olds		
	voth Pk AC	f0	voth Pk AC	f0	voth Pk AC	f0	voth Pk AC	f0	voth Pk AC	f0	voth Pk AC	f0
Pk	.3	RM	.8	DR	.6	DJ	.5	RM	.6	DR	.5	DJ
AC					-.7				.6			
f0	.8	.3	.5	.6	.8	.5	.4	.4	.5	.6	.4	
Pres			-.4	-.5	-.6							
Pk		JG	-.1	MS	.4	SS		JG		MS		SS
AC	.5				-.6				S A M E		-.6	
f0		.6		.7	.5				(All VOTH>0)			
Pres		.5	-.4									
Pk		DH	-.3	PC	.4	HJ		DH		PC		HJ
AC												
f0	.5	-.4	.3	.4		-.5					-.5	-.7
Pres		.3	-.3	.4		.3						
Pk	.4	SL	.2	DB		EC		SL		DB		EC
AC	-.5				-.5							
f0		.6	.5									
Pres		-.4	-.3		-.7	.8						
Pk		LR	.4	MD	.4	HH		LR		MD		HH
AC	-.5		.4		-.4				.4	.3		
f0		.5	.6	.3	.4	.4			.4	.8		.3
Pres		.3	.8	.5						.6		
Pk		ED		MP		LEZ		ED		MP		LEZ
AC	-.4		.4		-.4							
f0	.5	-.3				.5						
Pres		.3	.3	.4								
Pk		BG	.3	LK		MM		BG		LK		MM
AC	-.3		.2	.3	-.4				S A M E			
f0		.6	.4			.7			(All VOTH>0)			
Pres						.5						

Diagonal shaded areas indicate the redundant half of the matrix; other shading indicates that analyses could not be performed because of insufficient data (no pressure signal or few VOTH>0)

Table 3.11: Within-subject correlations on measures of /h/

Matrices have been simplified by rounding r-values to a single digit and showing only significant ($p < .05$, in bold face) or near-significant ($p < .10$, in plain face) results. Correlations of variables with themselves ($r=1$) are not shown. See text for discussion.

AM2-JG	/h/ pk	ACflow	onset f0	% VOIh=0
ACflow	+.5			100%
f0 On		+.6		
Pres		+.5		
AM5-LR	/h/ pk	ACflow	onset f0	% VOIh=0
ACflow	-.5			100%
f0 On		+.5		
Pres		+.3		
AM7-BG	/h/ pk	ACflow	onset f0	% VOIh=0
ACflow	-.3			100%
f0 On		+.6		
Pres				
AF6-MP	/h/ pk	ACflow	onset f0	% VOIh=0
ACflow	+.4			100%
f0 On				
Pres	+.3	+.4		
AF2-MS	/h/ pk	ACflow	onset f0	% VOIh=0
ACflow				0%
f0 On		+.7		
Pres				
AF7-LK	/h/ pk	ACflow	onset f0	% VOIh=0
ACflow	+.3			0%
f0 On				
Pres				

Tables 3.12: Simplified correlation matrices for the 6 subjects who were uniform in their /h/ voicing characteristics

Table 3.13a: Correlations with VOTh

Men	RM	JG	DH	SL	LR	ED	BG	count	
								+	-
Pkflow	+3			+4				2	
ACflow				-5		-4			2
onset f0	+8		+5			+5		3	
Pres									
Women	DR	MS	PC	DB	MD	MP	LK	+	-
Pkflow		-1			+4		+3	2	1
ACflow				+2	+4		+2	3	
onset f0				+5	+6		+4	3	
Pres		-4							1
5-year-olds	DJ	SS	HJ	EC	HH	LEZ	MM	+	-
Pkflow	+6	+4	+4		+4			4	
ACflow	-7	-6		-5	-4	-4	-4		6
onset f0	+8	+5			+4			3	
Pres				-7					1

Table 3.13b: Correlations with Peak flow

Men	RM	JG	DH	SL	LR	ED	BG	count	
								+	-
ACflow	+3	+5		-7	-5		-3	2	3
onset f0				-3		-3			2
Pres			+3	+4		+3		3	
Women	DR	MS	PC	DB	MD	MP	LK	+	-
ACflow	+8		-3		+3	+4	+3	5	1
onset f0	+5				+3			2	
Pres	-4		-3	+3	+8	+3		3	2
5-year-olds	DJ	SS	HJ	EC	HH	LEZ	MM	+	-
ACflow	-4								1
onset f0	+5			-7	+4			2	1
Pres	+4							1	

Tables 3.13a-b: Correlations with VOTh and Peak flow for individual subjects

Table 3.13c: Correlations with ACflow

									<u>count</u>	
Men	RM	JG	DH	SL	LR	ED	BG		+	-
onset f0	+3	+6	-4	+6	+5		+6		5	1
Pres		+5		-6	+3				2	1
Women	DR	MS	PC	DB	MD	MP	LK		+	-
onset f0	+6	+7							2	
Pres	-5				+5	+4			2	1
5-year-olds	DJ	SS	HJ	EC	HH	LEZ	MM		+	-
onset f0	-6		-5			+5	+7		2	2
Pres			+3	+8			+5		3	

Table 3.13d: Correlations with Onset f0

									<u>count</u>	
Men	RM	JG	DH	SL	LR	ED	BG		+	-
Pres			+3	-4					1	1
Women	DR	MS	PC	DB	MD	MP	LK		+	-
Pres	-8		+4						1	1
5-year-olds	DJ	SS	HJ	EC	HH	LEZ	MM		+	-
Pres							+7		1	

Tables 3.13c-d: Correlations with ACflow and f0 for individual subjects

Token percentile values:

"L" means the token falls at or below the 10th percentile for that variable.
 "l" means the token falls at or below the 25th percentile for that variable.
 "h" means the token falls at or above the 75th percentile for that variable.
 "H" means the token falls at or above the 90th percentile for that variable.

subj	# of tokens	Peak /h/	AC flow	Ons. f0	Pres	% VOT=0
AF3-PC	#1	H		H		91%
	#2	H	L	L	L	
	#3	l		h	h	
AM3-DH	#1		L	H	h	92%
	#2					
	#3	H	L	H	H	
	#4	L				
AM4-SL	#1	H	L			93%
	#2	h	L	H	H	
5M4-MM	#1		L			93%
	#2		L	L		
	#3	H	l			
5M3-LEZ	#1		L	l		74%
	#2	h		L		
	#3		l	L		
	#4	l	L			
	#5		l			
	#6			h		
AM1-RM	#1	L	L			60%
	#2		l			
	#3		L			
	#4	h	h			
	#5	H	H	H		
	#6		H			
	#7					
	#8	L	h	h		
	#9			h		
	#10	l		H		
	#11			h		
	#12	l				
	#13	h		h		
	#14			h		
	#15			H		
	#16			H		
	#17	L	h	h		
	#18			H		
	#19	h	h	h		
5F2-EC	#1		L	h		67%
	#2		l		l	
	#3					
	#4				L	
sums (of 41/16)	H	6	2	9	2	
	h	5	4	10	2	
	l	4	5	1	1	
	L	4	12	3	2	

Tables 3.14: Token percentile values for subjects with mostly VOT=0

Token percentile values:

- "L" means the token falls at or below the 10th percentile for that variable.
 "l" means the token falls at or below the 25th percentile for that variable.
 "h" means the token falls at or above the 75th percentile for that variable.
 "H" means the token falls at or above the 90th percentile for that variable.

subj	# of tokens	Peak /h/	AC flow	Ons. f0	Pres	% VOT=0
AF4-DB	#1			l	H	17%
	#2	h	L	l	H	
	#3		L		h	
	#4		L	L		
	#5	l		L	l	
	#6	L		l		
	#7	L	h			
	#8	H		L	H	
AF5-MD	#1	L	h	L		13%
	#2			L	l	
	#3	l		L		
	#4	L			L	
	#5		L			
5F3-HH	#1	l	H	l		19%
	#2			L		
	#3					
	#4	L	L	L		
	#5	l		L		
	#6		h	l	H	
	#7	H	h	h		
	#8	l	h	L		
5M1-DJ	#1	l	h	l		34%
	#2	l	h	L		
	#3	l				
	#4	L		l	l	
	#5	L		L		
	#6	l	H			
	#7		h	L	h	
	#8	L	H	l	l	
	#9		H			
	#10		h	l	L	
	#11			L		
	#12		h	l		
	#13		H	l		
sums (of 34)	H	2	5	0	4	
	h	1	10	1	2	
	l	9	0	11	4	
	L	8	4	14	2	

Tables 3.15: Token percentile values for subjects with mostly VOT_h>0

Token percentile values:

- "L" means the token falls at or below the 10th percentile for that variable.
 "l" means the token falls at or below the 25th percentile for that variable.
 "h" means the token falls at or above the 75th percentile for that variable.
 "H" means the token falls at or above the 90th percentile for that variable.

subj	# of tokens	Peak /h/	AC flow	Ons. f0	Pres	% VOT=0	
AM6-ED	#1	<i>h</i>		<i>h</i>		63%	
	#2	<i>h</i>		<i>l</i>			
	#3			L	L		
	#4						
	#5		<i>l</i>	<i>h</i>			
	#6	L	<i>l</i>	H	L		<i>h</i>
	#7			H			<i>h</i>
	#8	<i>l</i>	L				
	#9		L	H			<i>h</i>
	#10						<i>l</i>
	#11						<i>h</i>
	#12	L		H			
	#13		<i>l</i>	<i>h</i>			
	#14		<i>l</i>	L			<i>l</i>
	#15	H	<i>h</i>	<i>h</i>	<i>h</i>		
5M1-SS	#1	<i>h</i>			H	55%	
	#2	<i>l</i>		H	<i>l</i>		
	#3	<i>l</i>	L	L			
	#4	<i>h</i>					
	#5	H	L	H			<i>h</i>
	#6		<i>l</i>				
	#7	<i>h</i>	<i>l</i>	<i>h</i>			
	#8						
	#9	<i>h</i>	<i>h</i>	<i>h</i>	L		
	#10		<i>l</i>		L		
5F1-HJ	#1	H				50%	
	#2	L	L		<i>h</i>		
	#3		<i>l</i>	<i>h</i>	<i>l</i>		
	#4	<i>h</i>					
	#5	<i>h</i>	<i>h</i>	<i>l</i>	H		
	#6	L			<i>l</i>		
	#7		<i>h</i>	L			
	#8						
	#9		<i>l</i>	H	<i>h</i>		
	#10	H	<i>h</i>				
	#11	<i>h</i>	L				
	#12	<i>h</i>			<i>l</i>		
	#13		L	<i>h</i>			

sums	H	4	0	7	2
(of 38)	<i>h</i>	10	5	8	6
	<i>l</i>	3	9	2	6
	L	4	7	4	4

Tables 3.16: Token percentile values for subjects with split VOTh distributions

Token percentile values:

- "L" means the token falls at or below the 10th percentile for that variable.
 "l" means the token falls at or below the 25th percentile for that variable.
 "h" means the token falls at or above the 75th percentile for that variable.
 "H" means the token falls at or above the 90th percentile for that variable.

time in session	subj	# of tokens	Peak /h/	AC flow	Ons. f0	Pres	% VOT=0
early	AF1-DR	#1	<i>h</i>	H	<i>h</i>	L	25%
		#2	<i>h</i>	H		<i>l</i>	
		#3	<i>h</i>		H	L	
		#4		<i>h</i>	H		
mid		#5			L	<i>h</i>	
		#6			<i>l</i>	H	
late		#7	<i>l</i>				
		#8	<i>l</i>	L	<i>l</i>		
		#9	L	<i>l</i>	L		

Table 3.17: Token percentile values for one subject who varied across the recording session

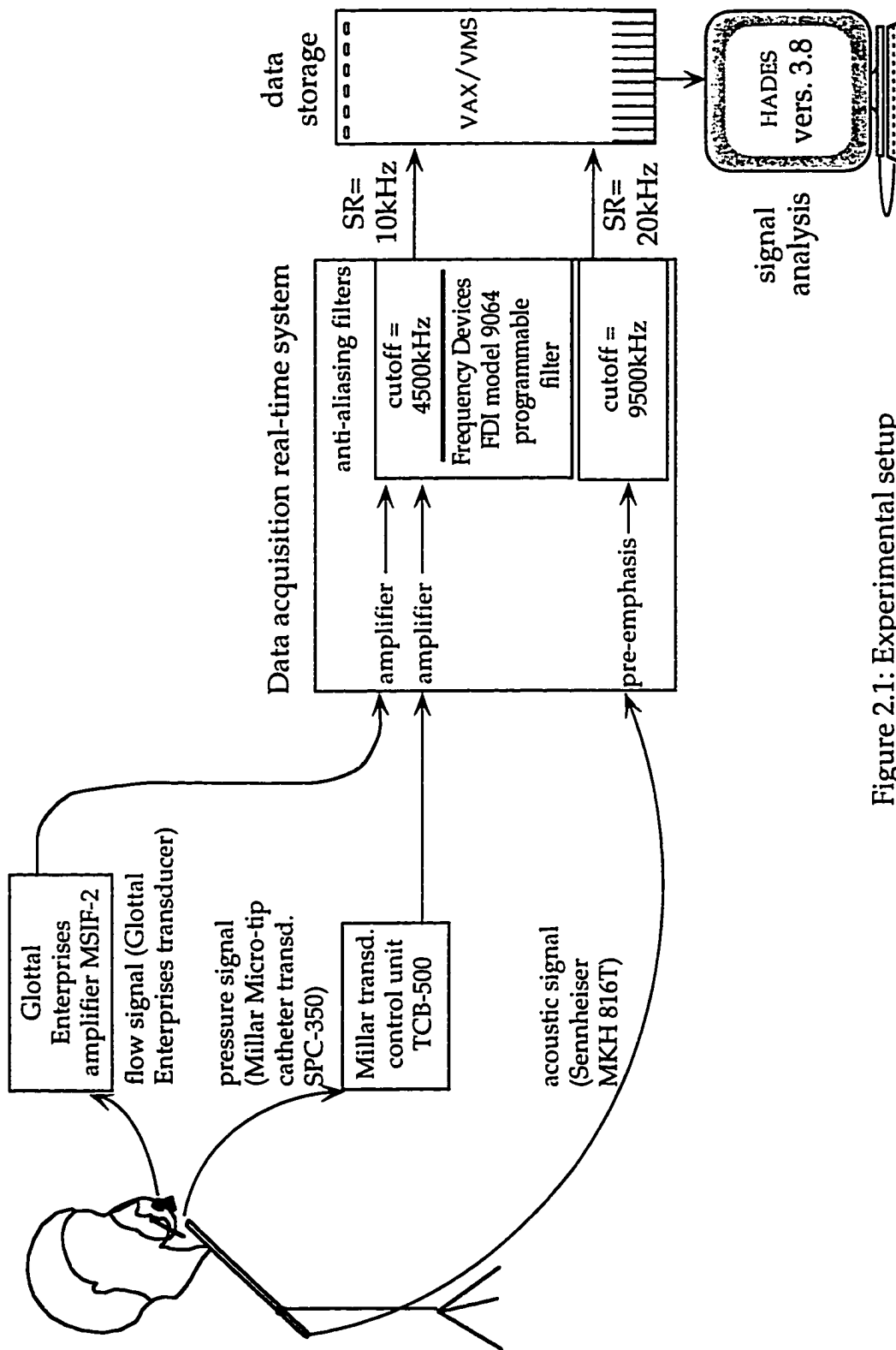


Figure 2.1: Experimental setup

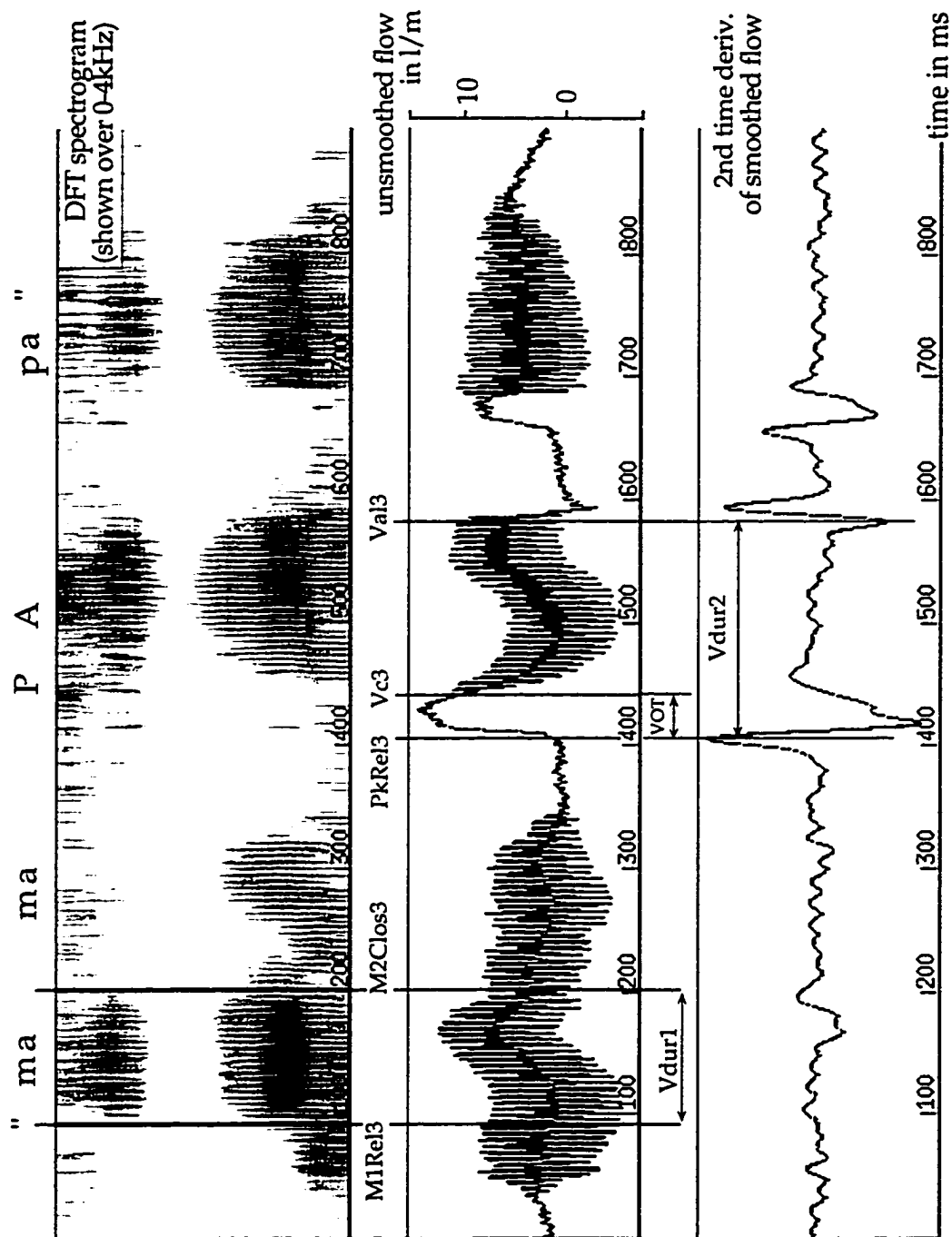


Figure 2.2: Labels used to define stop VOTs and vowel duration

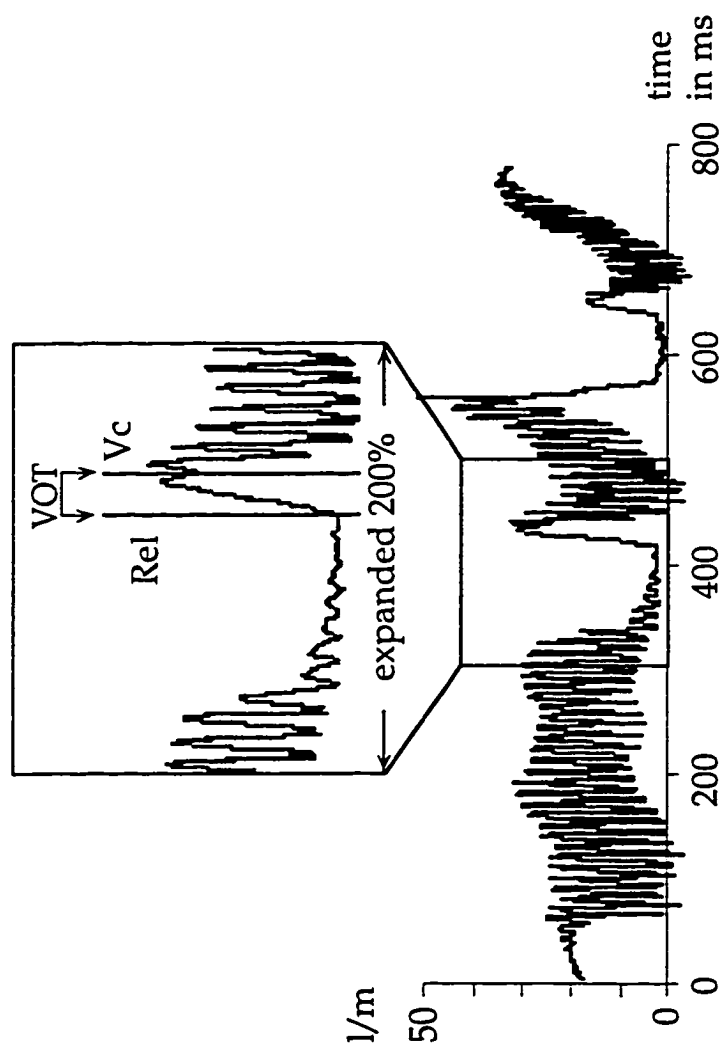


Figure 2.3: Pulse coincident with burst yielding positive VOT in a voiced stop

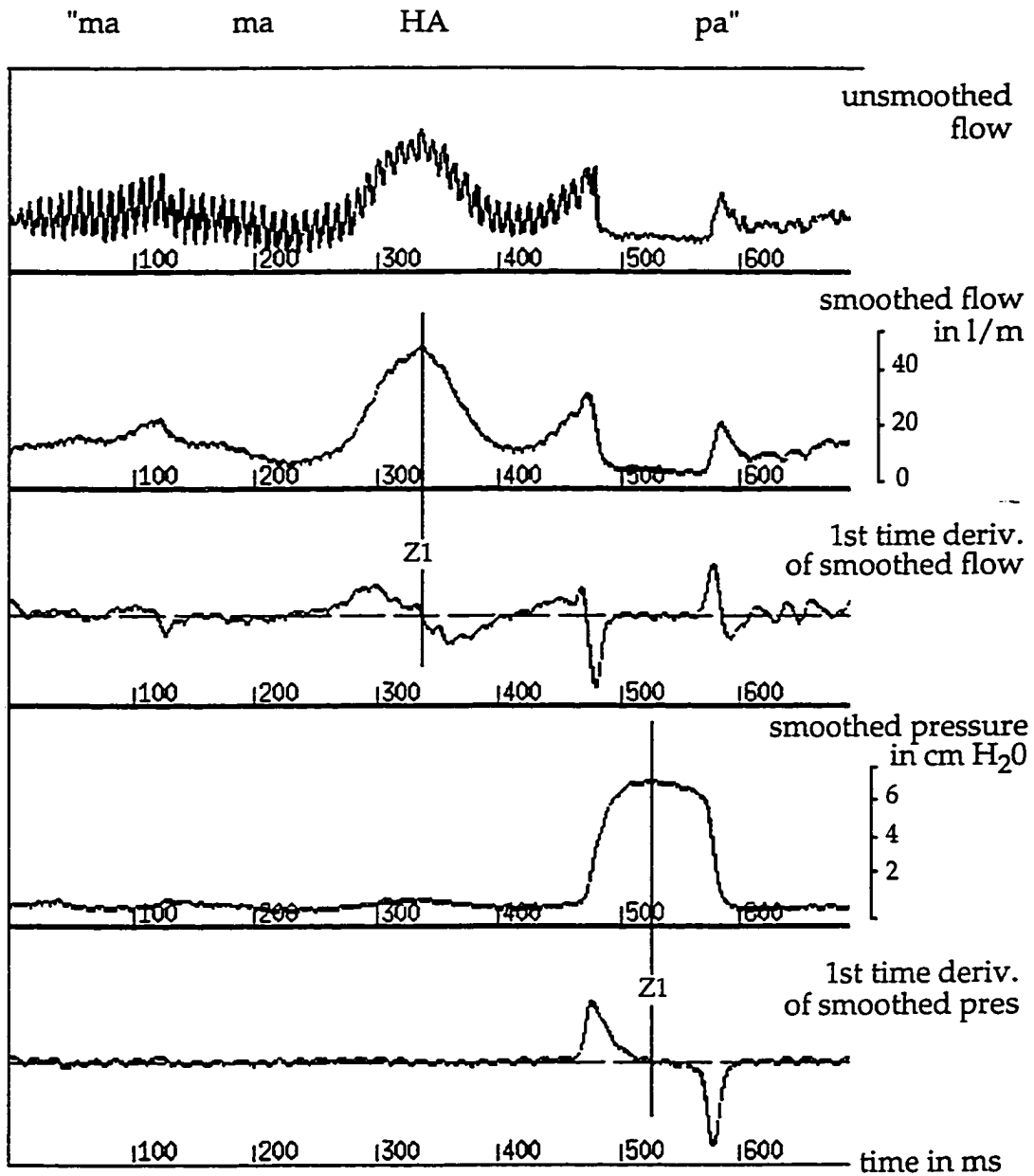


Figure 2.4: Using velocity signals to define flow and pressure peaks

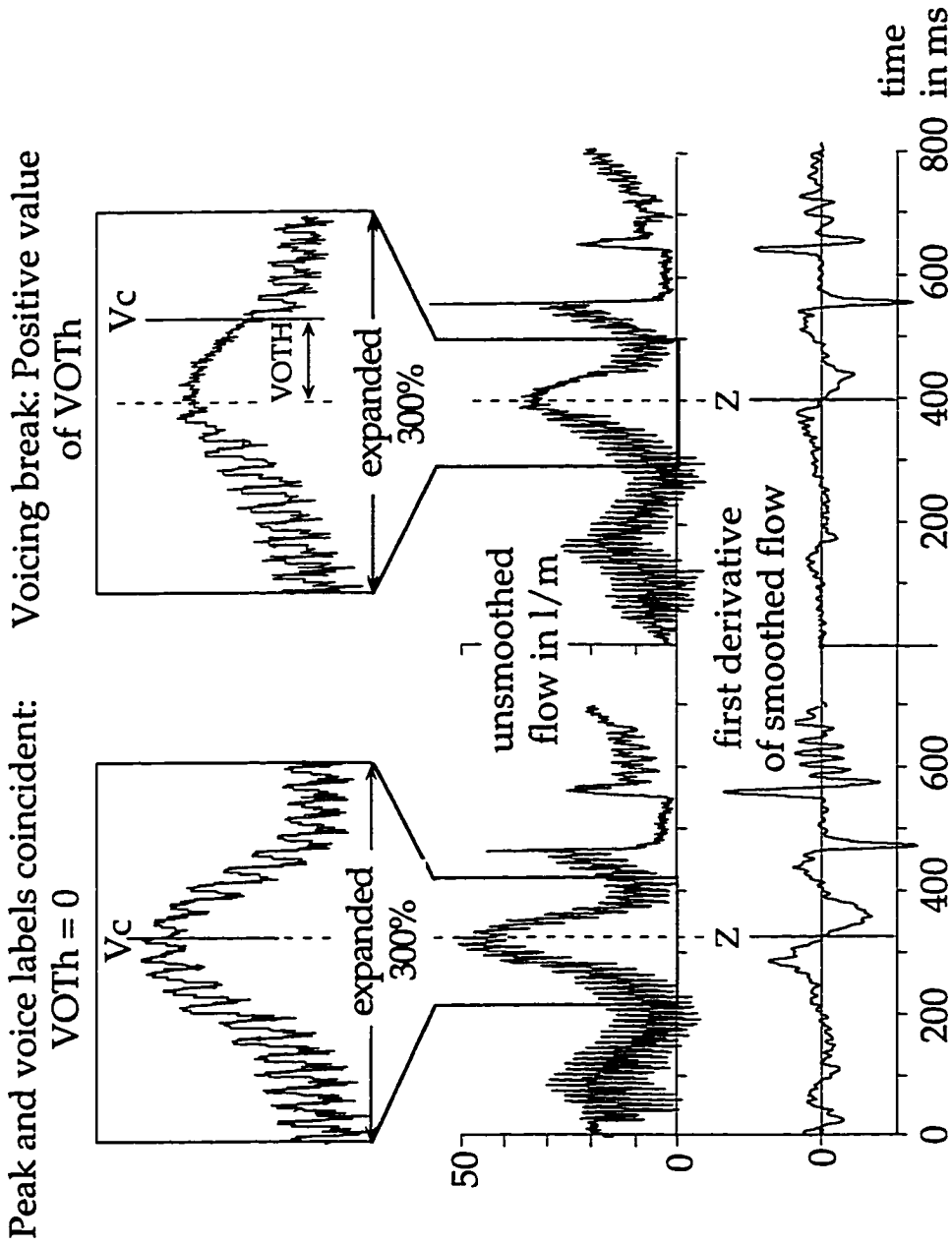


Figure 2.5: Labeling VOTh for tokens with and without voicing breaks

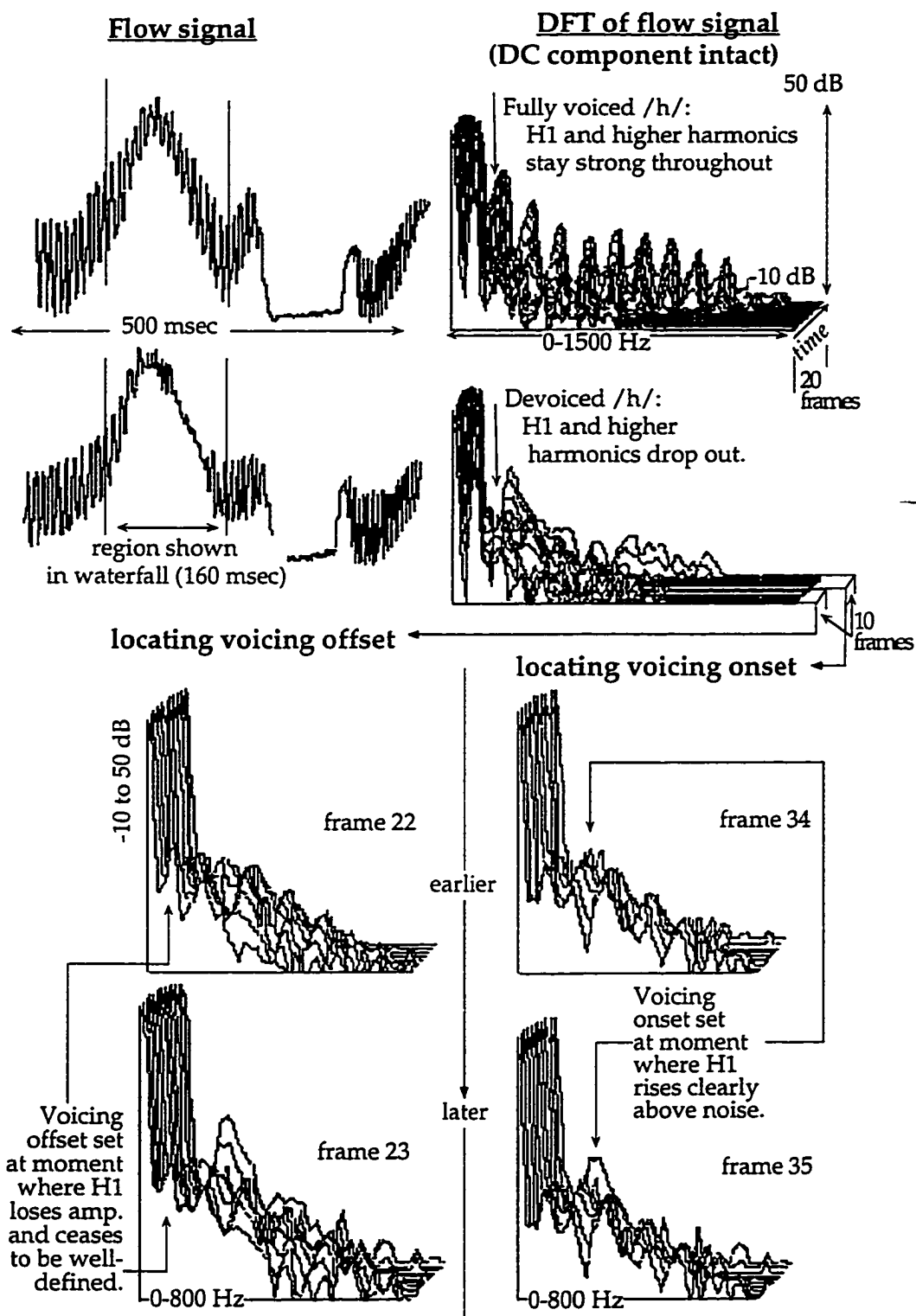


Figure 2.6: Defining voicing offset and onset in /h/ from waterfall displays

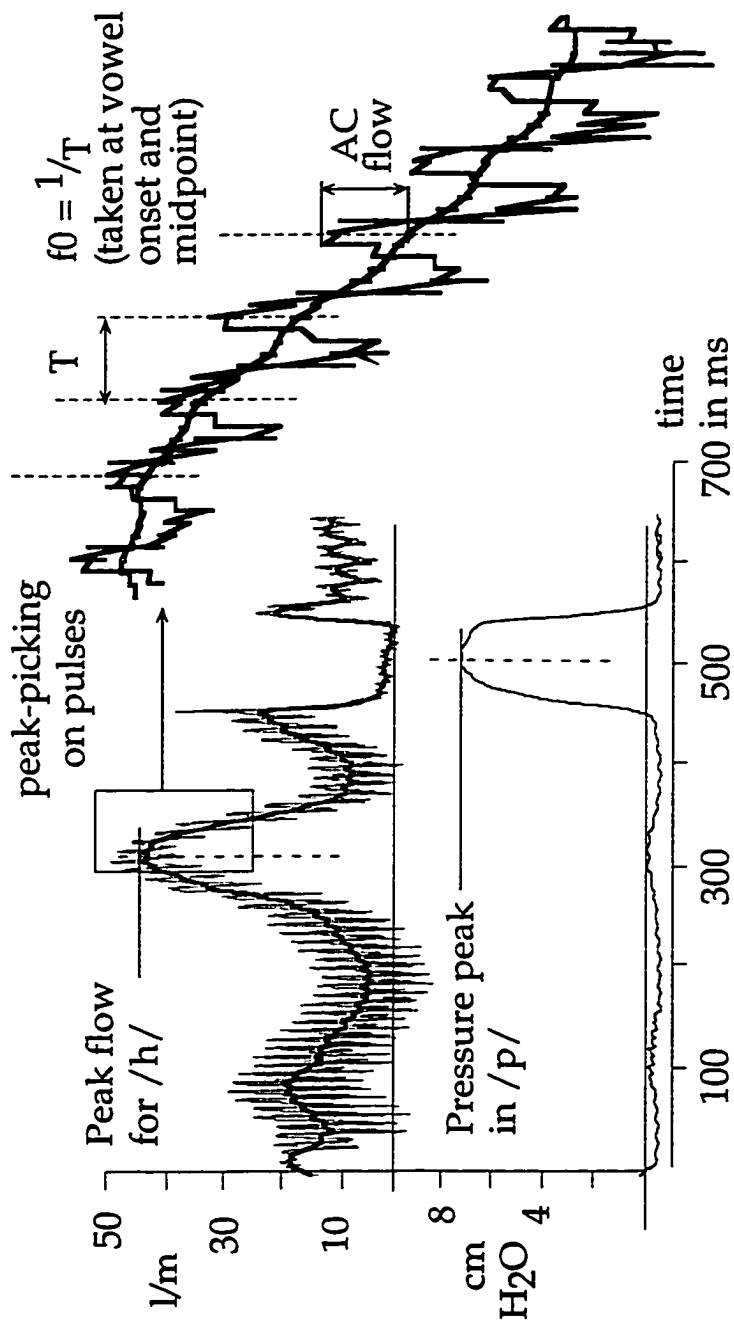


Figure 2.7: Defining measures for correlation with VOT_h

i

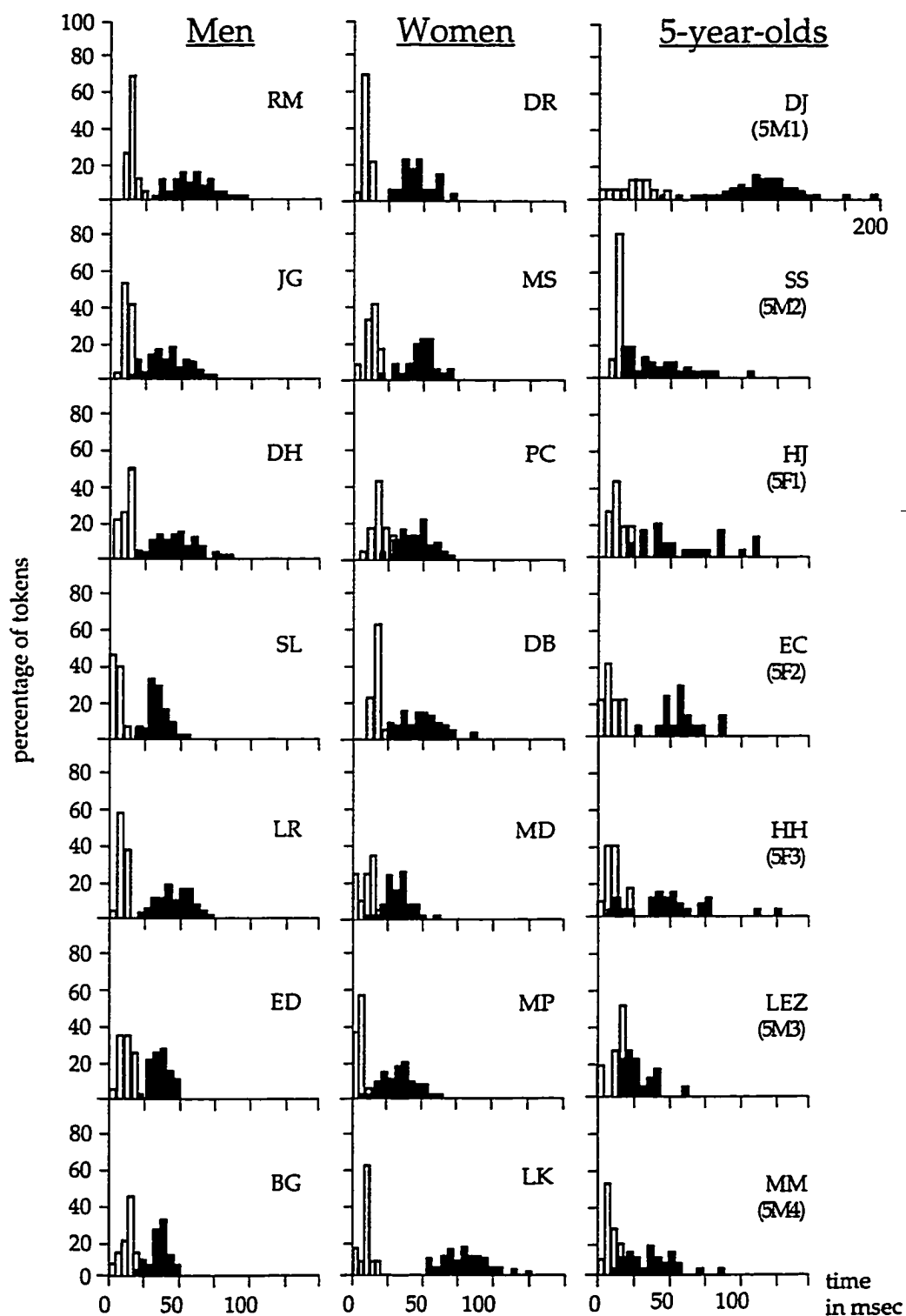


Figure 3.1: VOT for /b/ and /p/, all subjects
 /b/=□ /p/=■

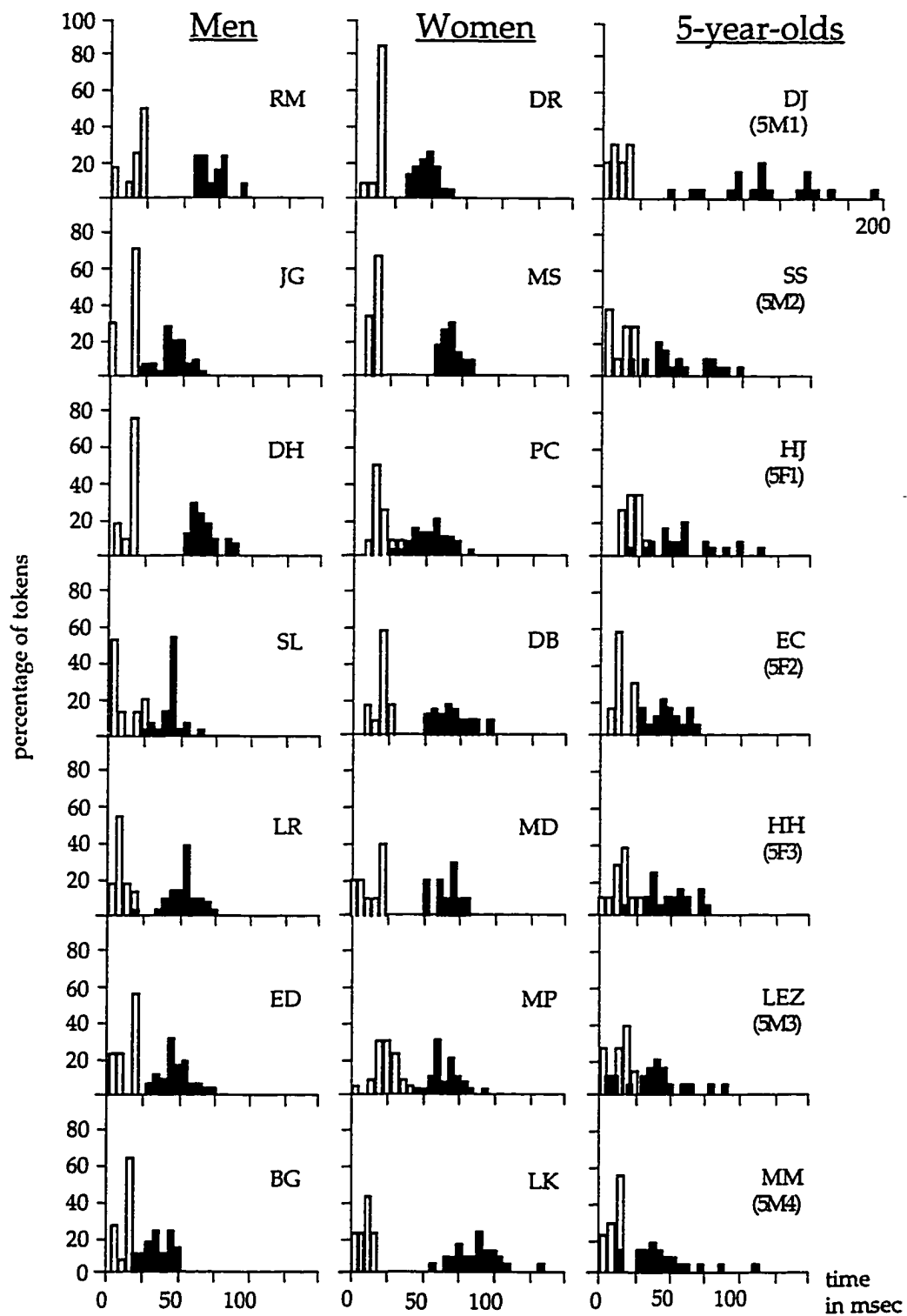


Figure 3.2: VOT for /d/ and /t/, all subjects
 /d/=□ /t/=■

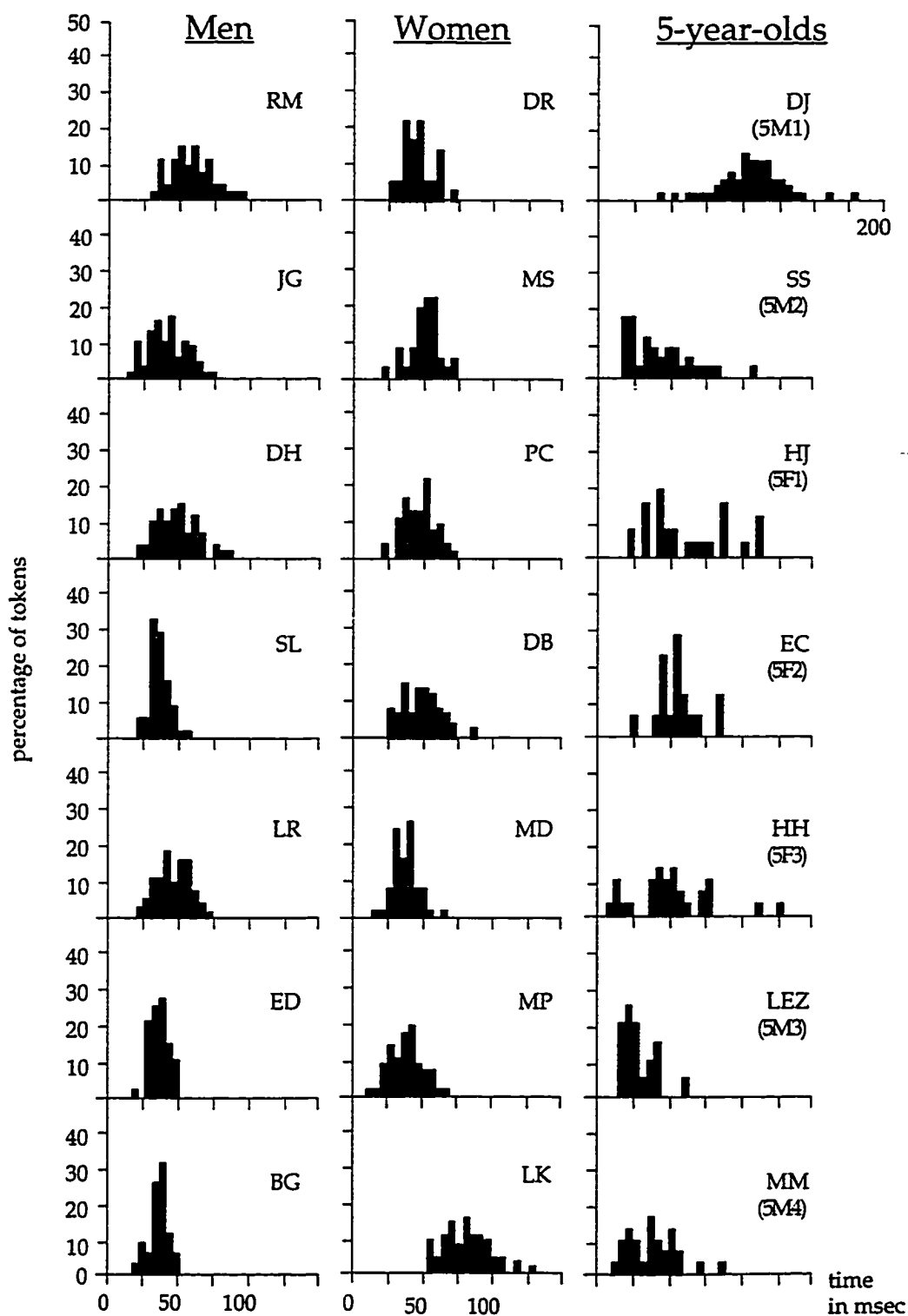


Figure 3.3: VOT for /p/, all subjects (expanded scale)

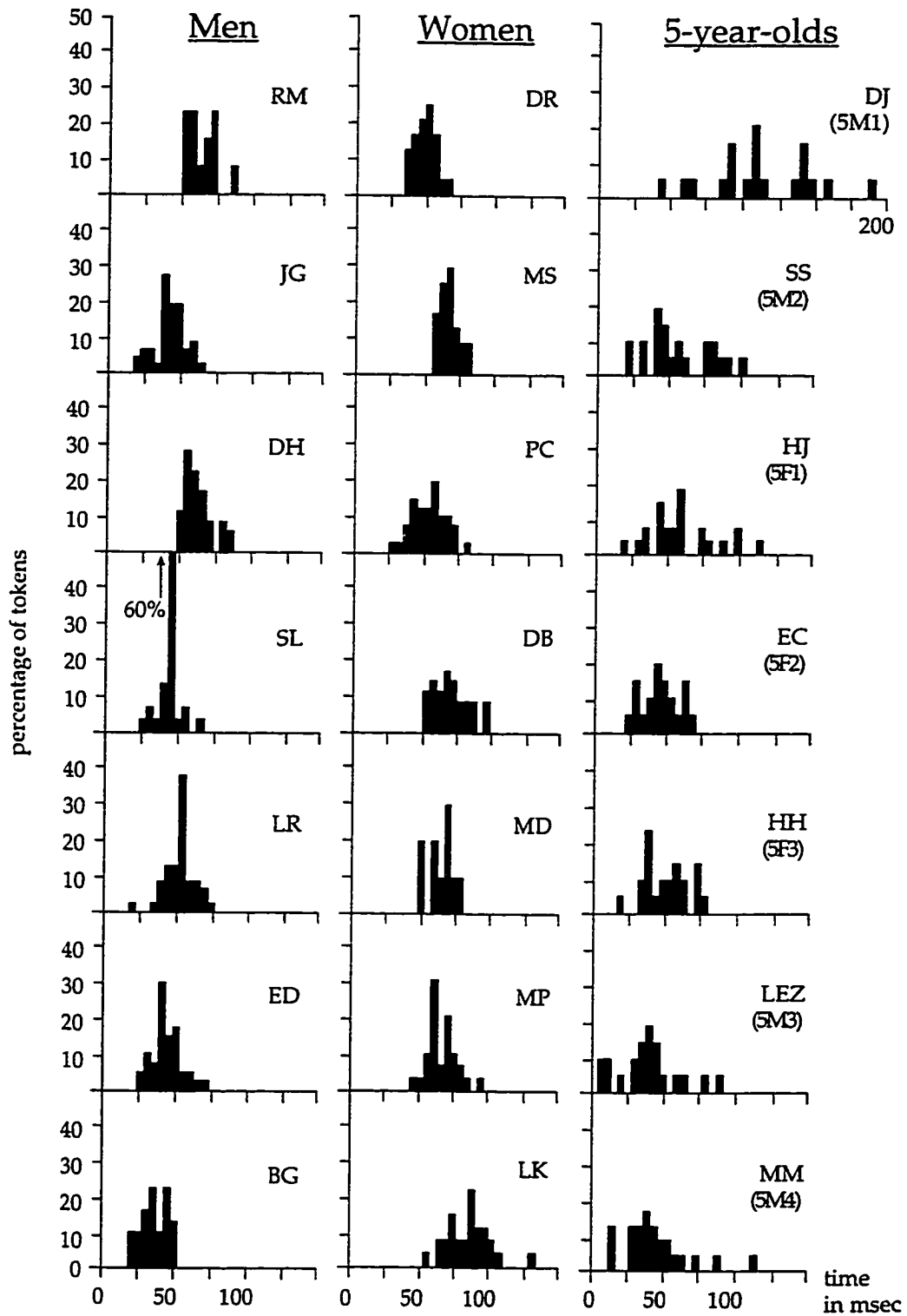


Figure 3.4: VOT for /t/, all subjects (expanded scale)

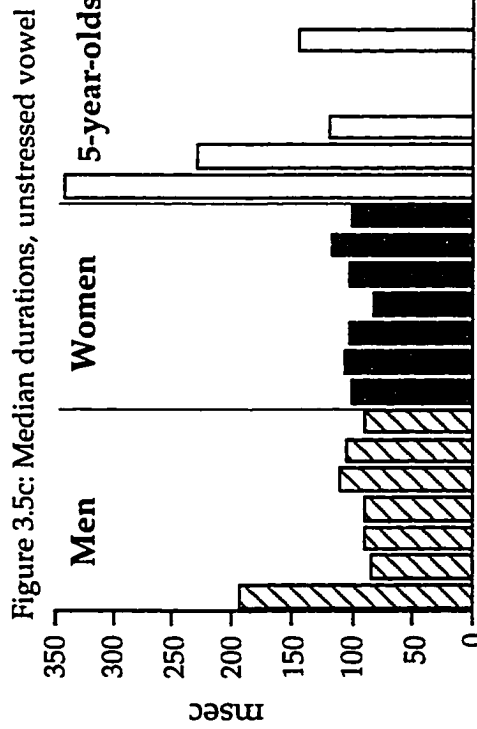
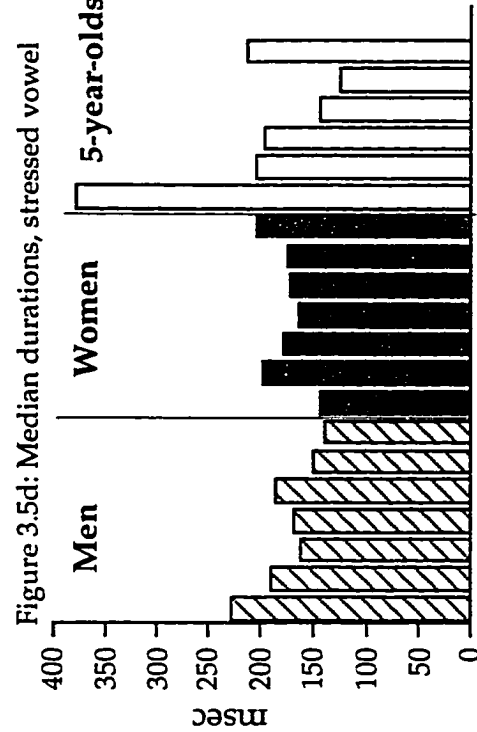
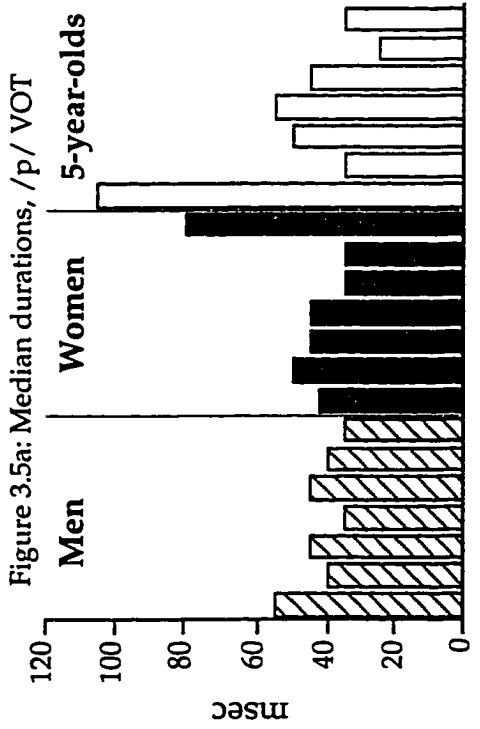
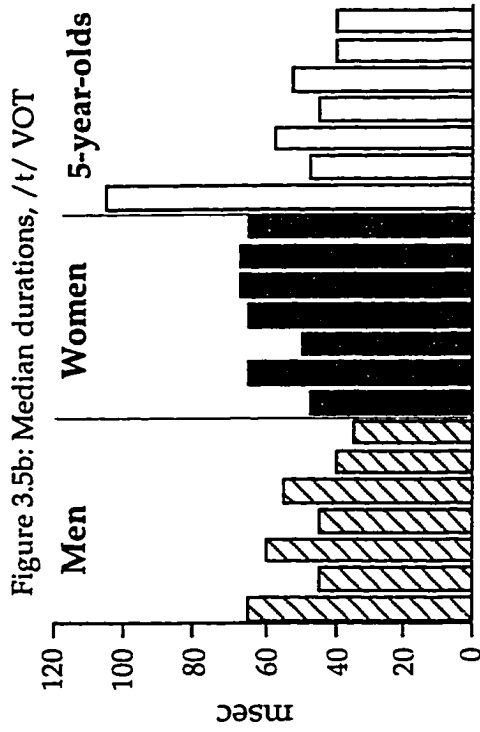


Figure 3.5: Median durations for /p, t/ VOTs, and vowel durations, all subjects
Individuals are ordered numerically within each group.

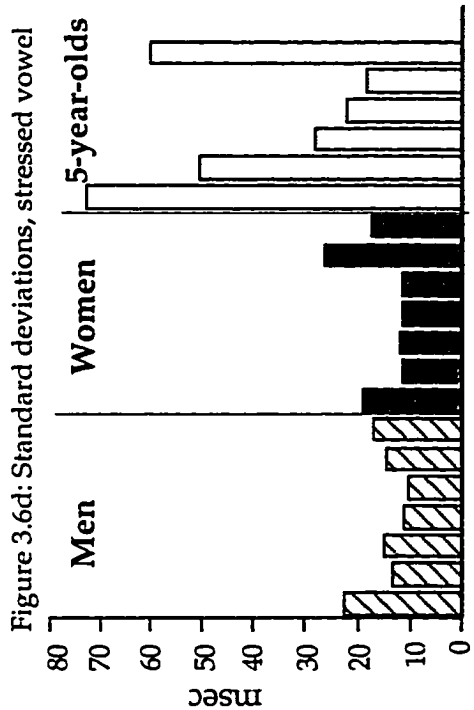
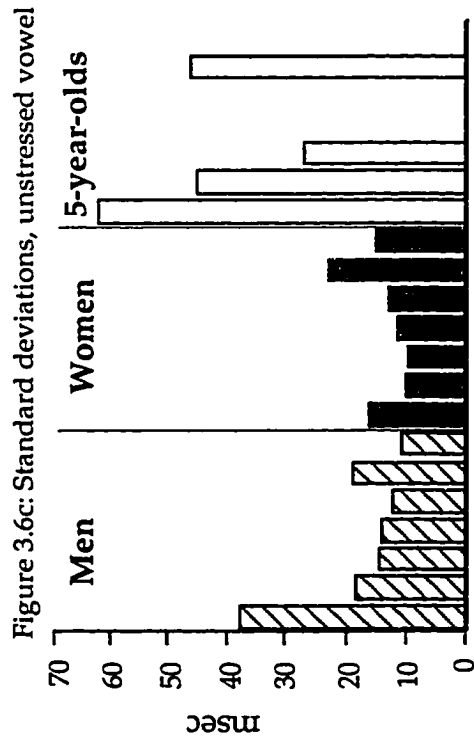
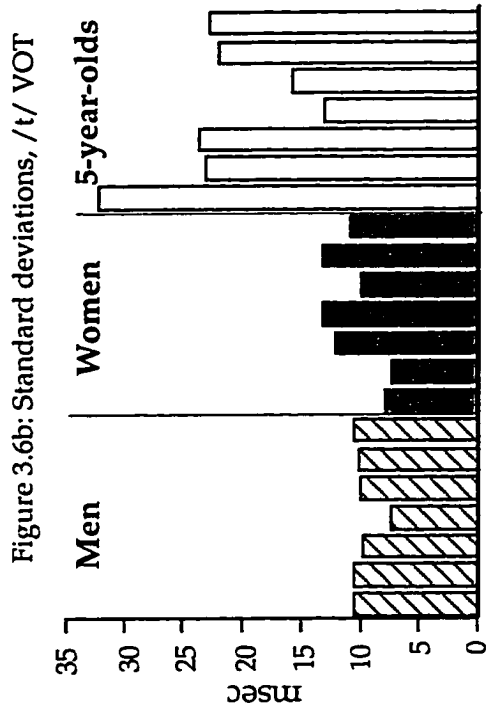
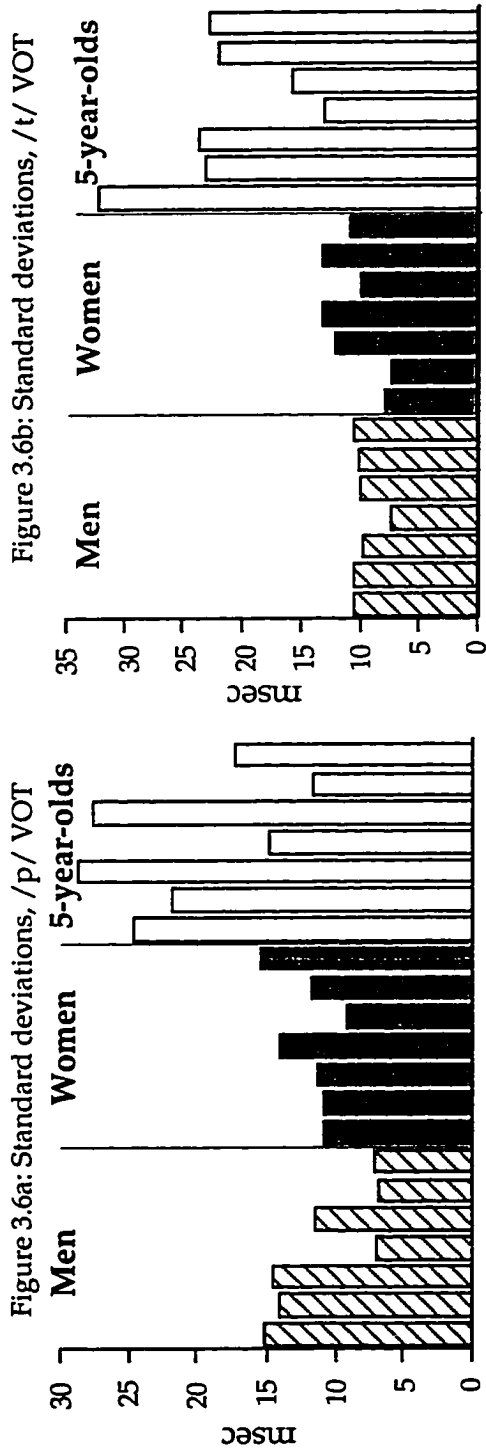


Figure 3.6: Standard deviations for /p, t/ VOTs, and vowel durations, all subjects
Individuals are ordered numerically within each group

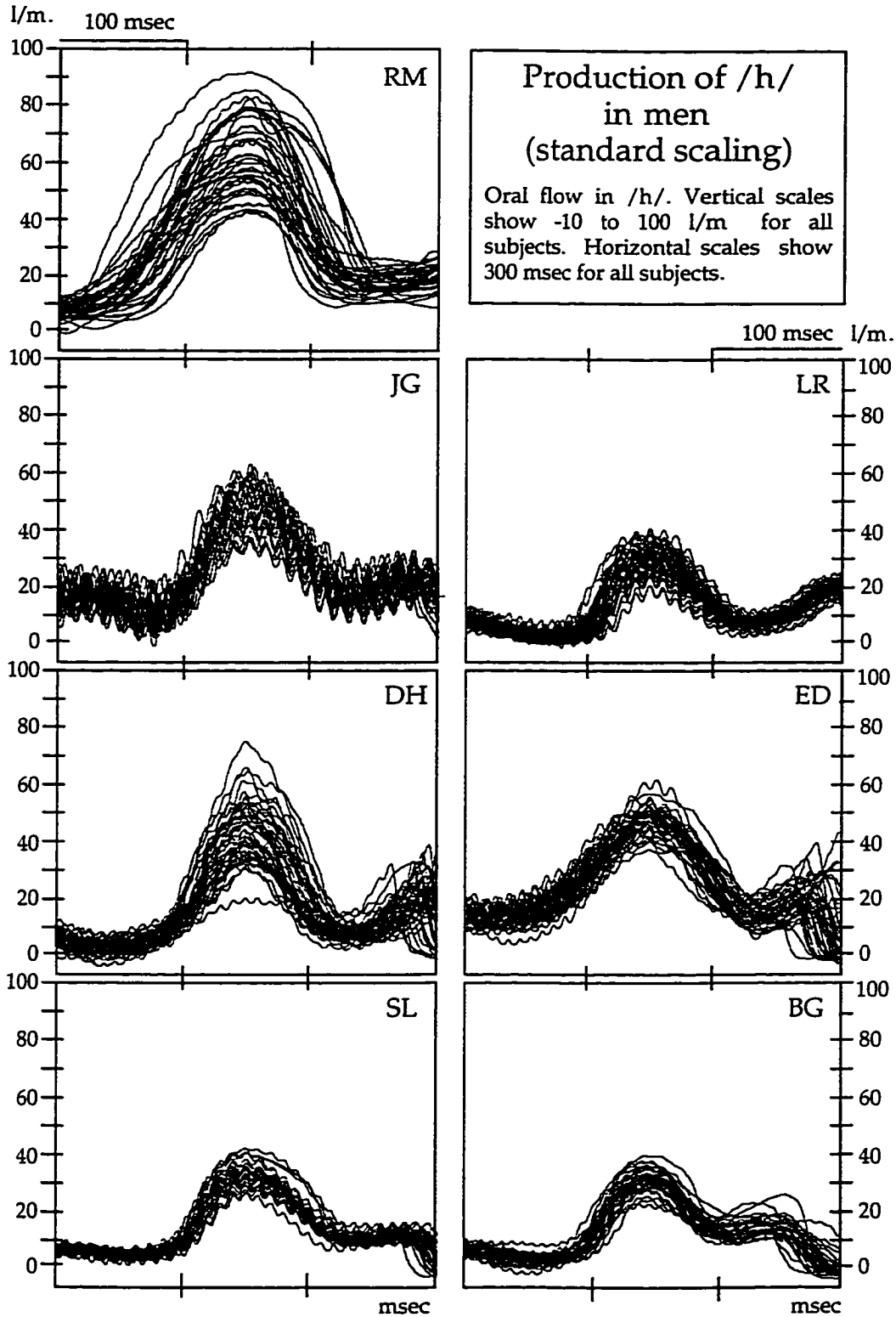


Figure 3.7a: Adult males' productions of /h/ (standard scaling)

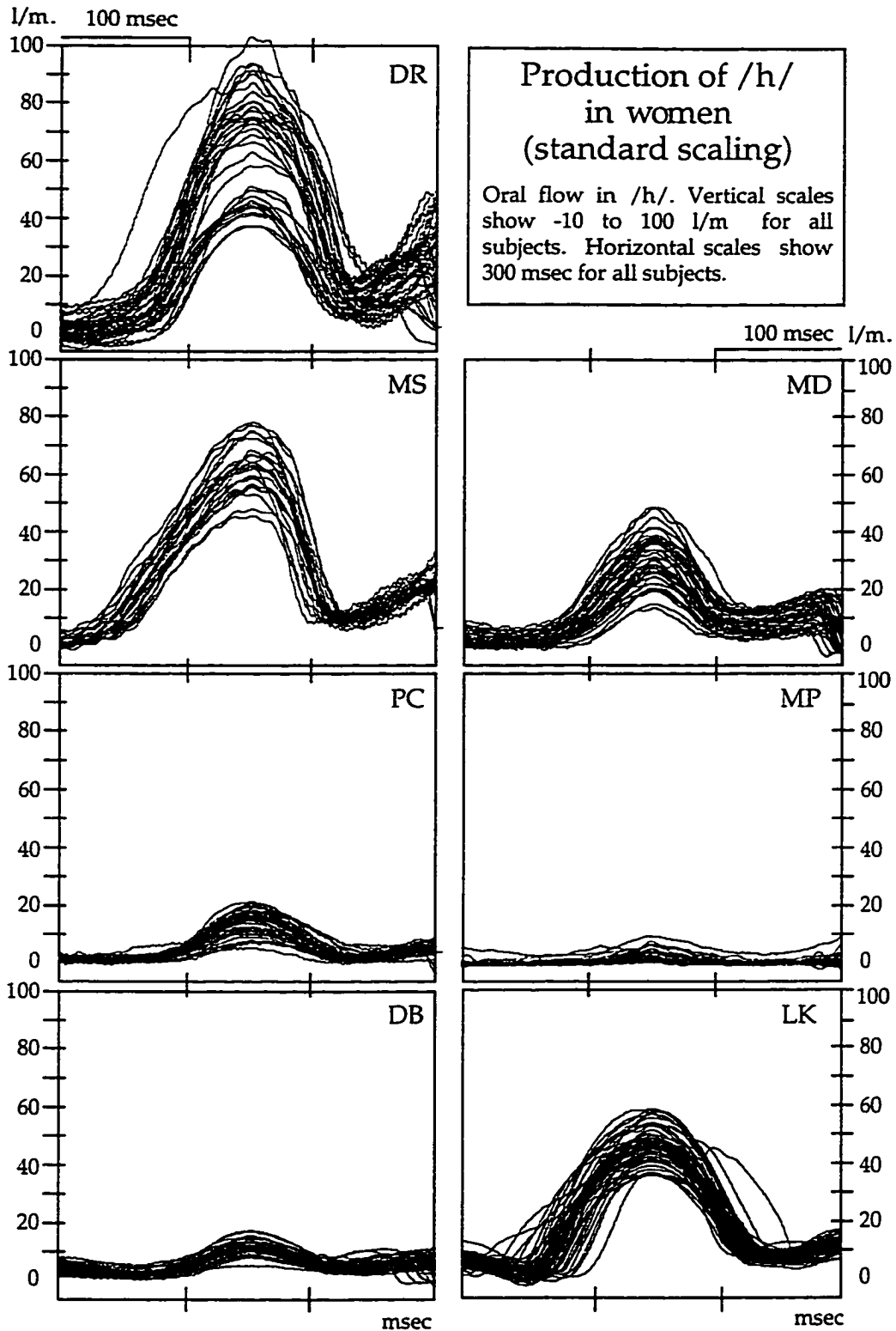


Figure 3.7b: Adult females' productions of /h/ (standard scaling)

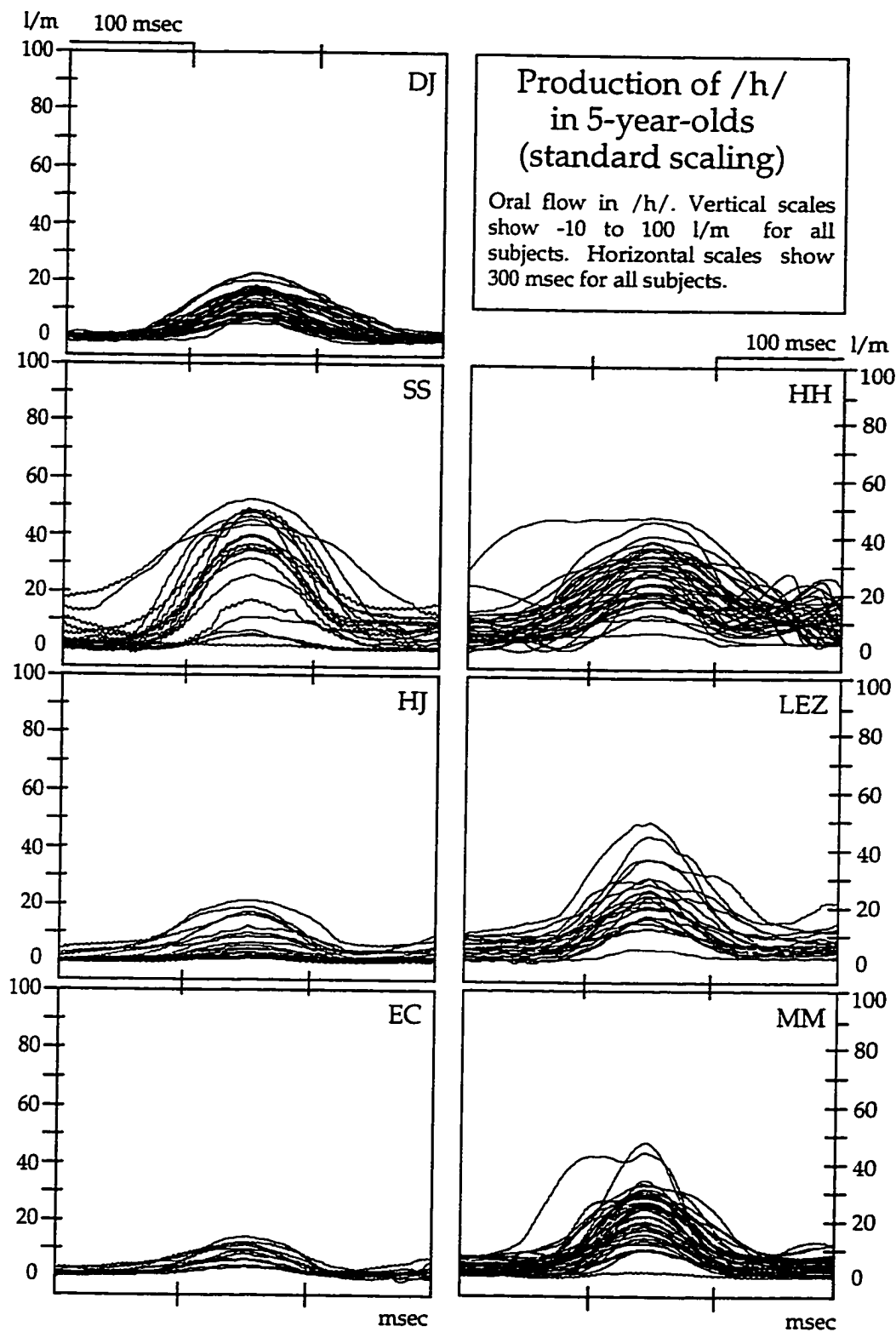


Figure 3.7c: 5-year-olds' productions of /h/ (standard scaling)

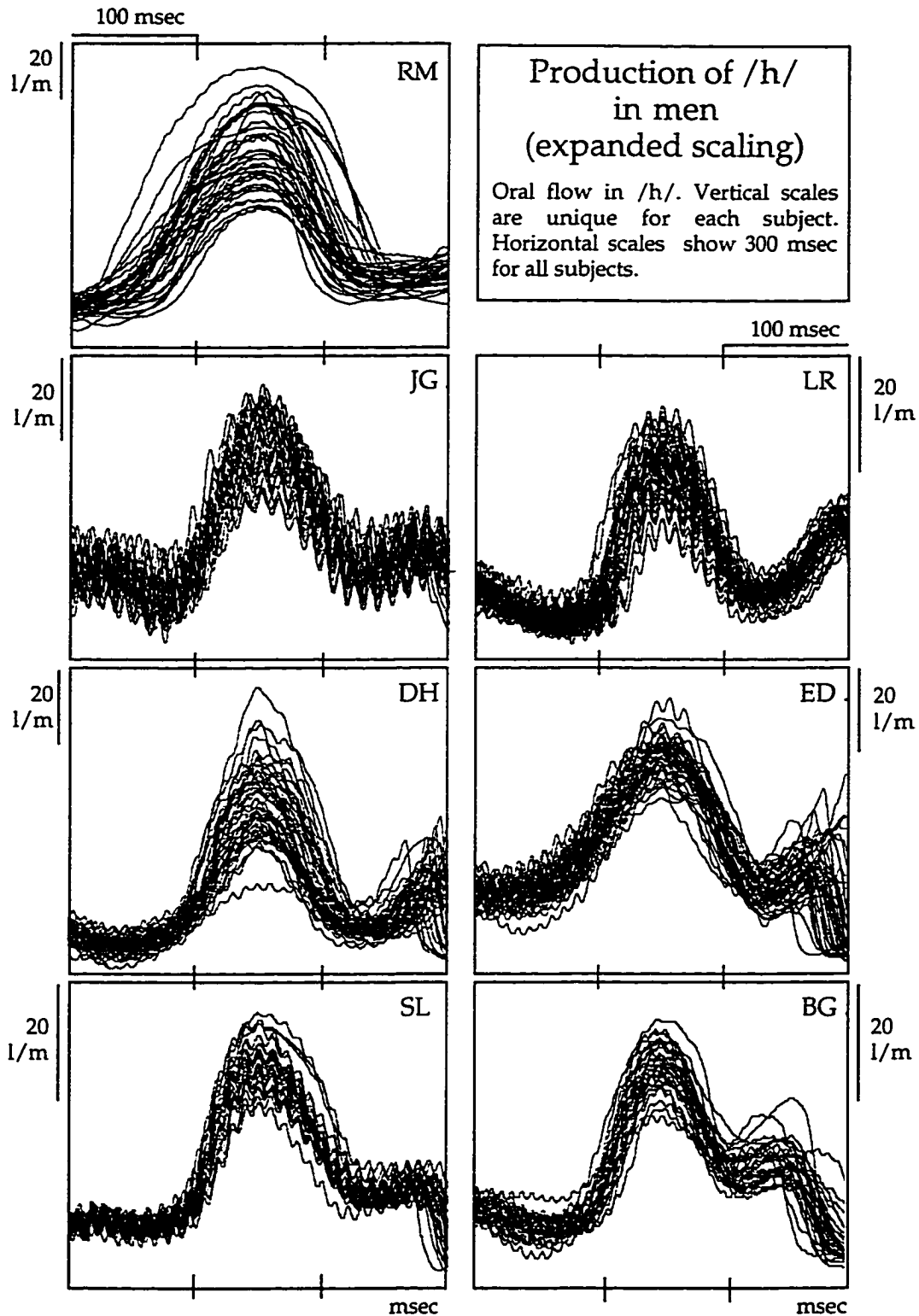


Figure 3.8a: Adult males' productions of /h/ (expanded scaling)

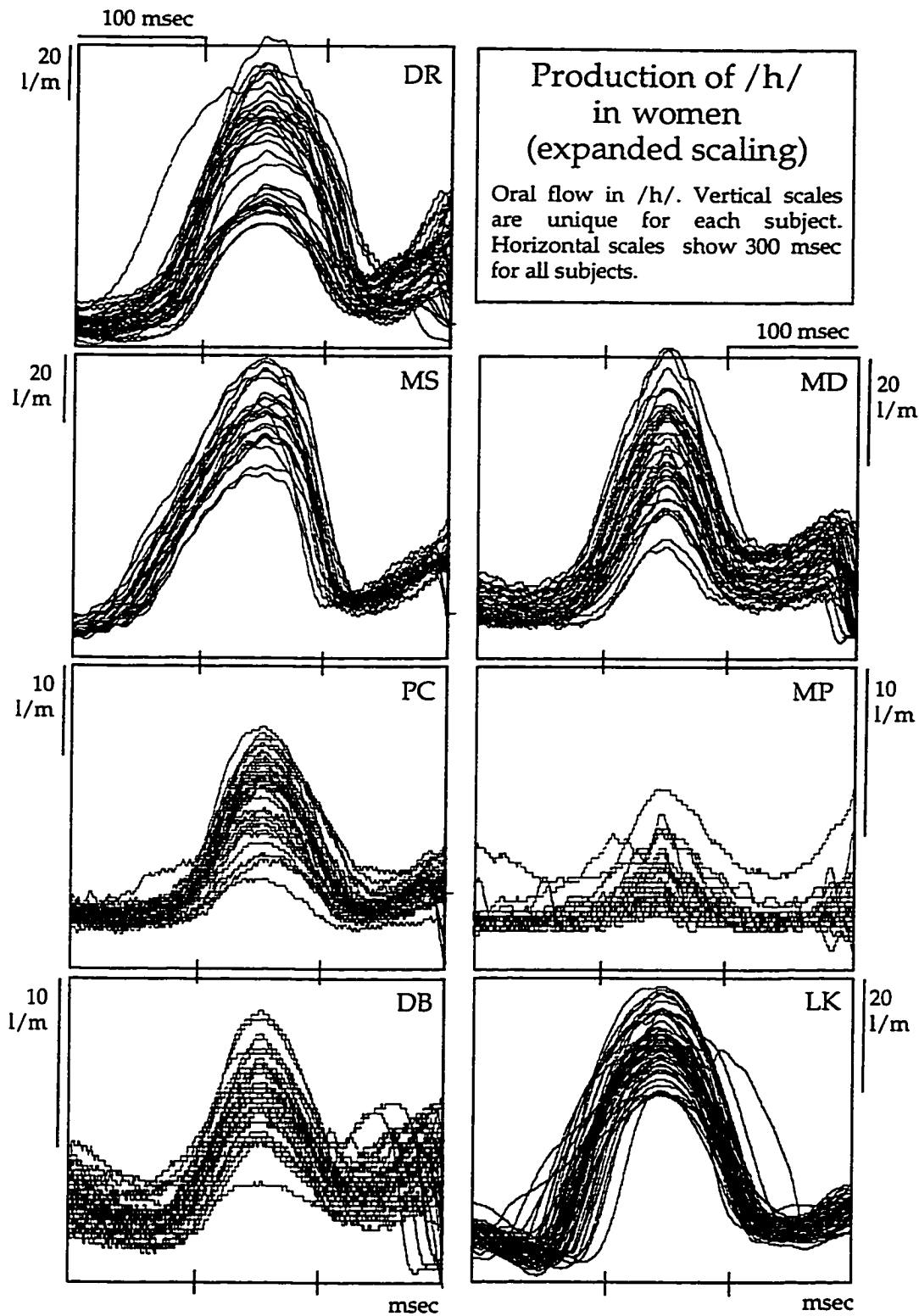


Figure 3.8b: Adult females' productions of /h/ (expanded scaling)

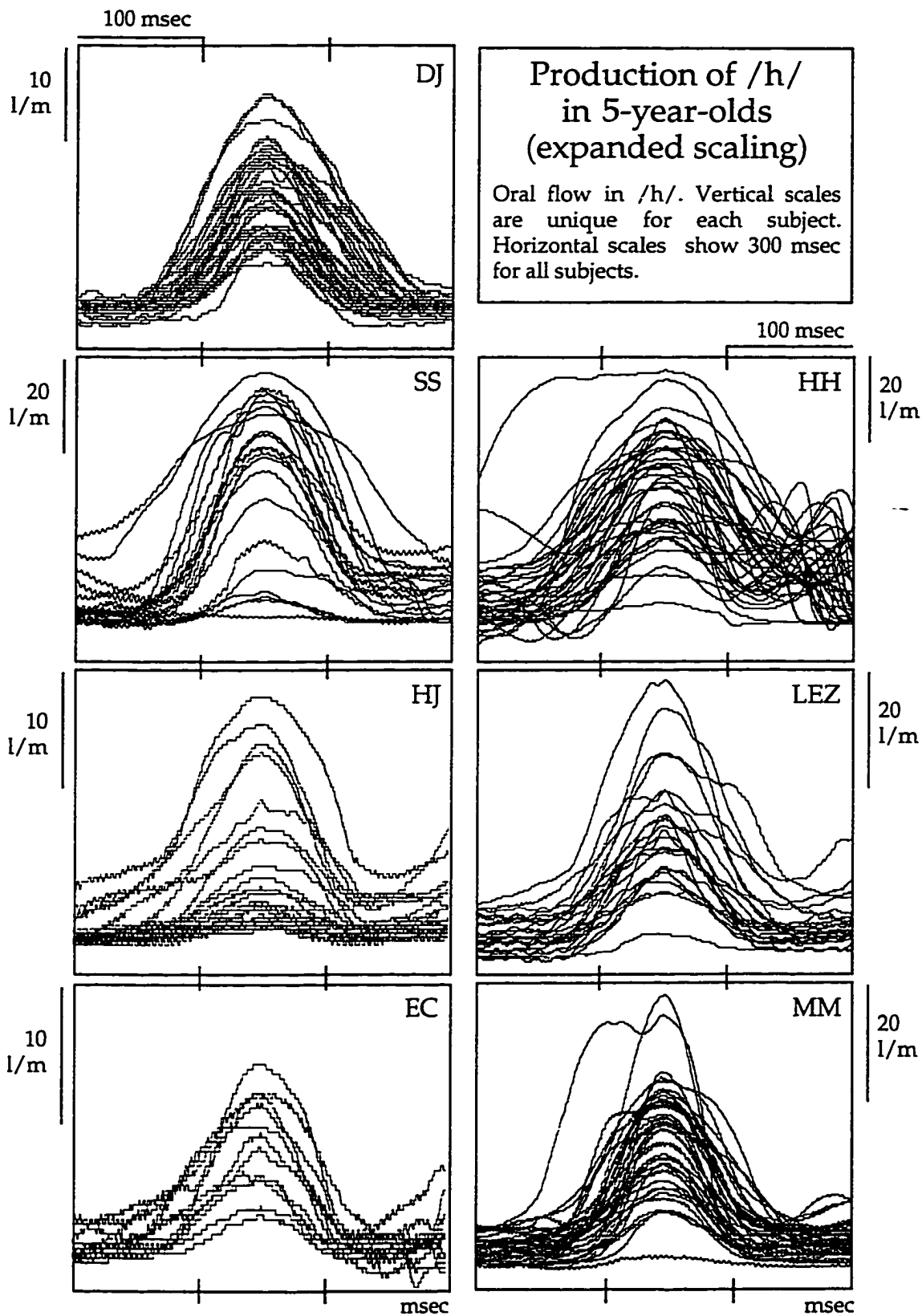


Figure 3.8c: 5-year-olds' productions of /h/ (expanded scaling)

Figure 3.9: Median /h/ flow peak as a function of median pressure peak for each subject

◻ = Men, ● = Women, ▼ = 5-year-olds

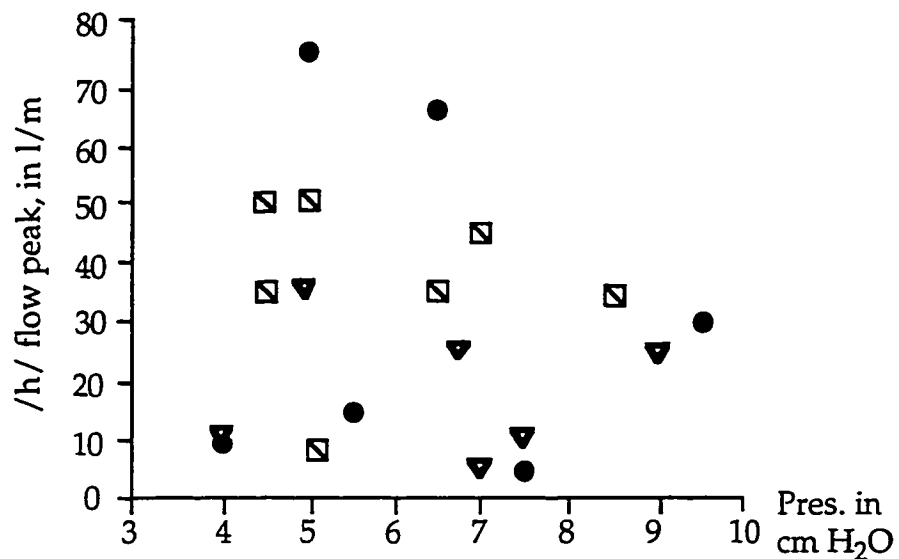
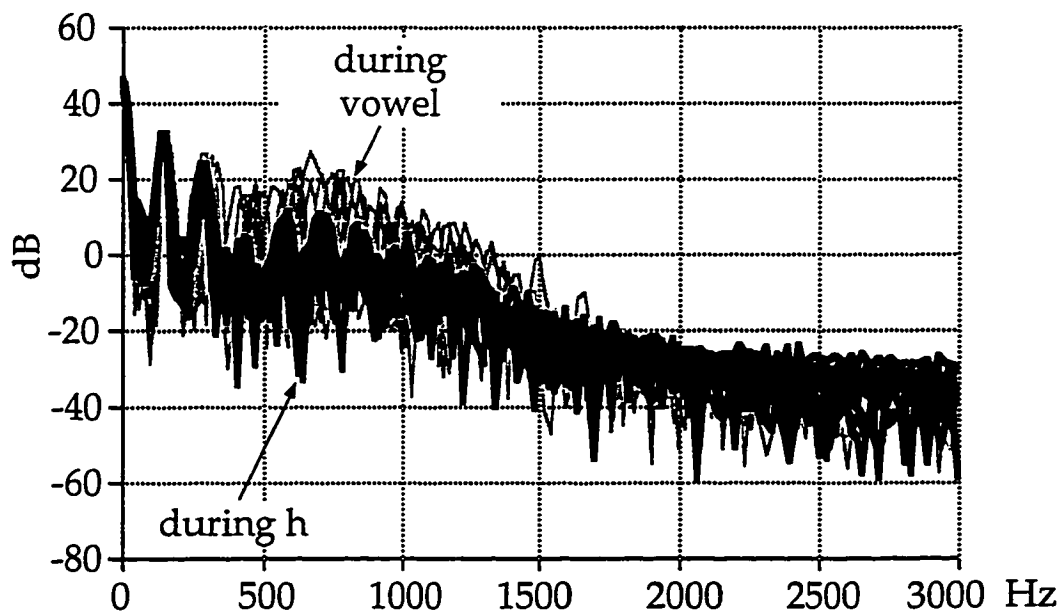


Figure 3.10: DFT spectra for a subset of AF6-MP's /h/'s (dark traces) and subsequent vowels (light traces)



Figures 3.9–3.10

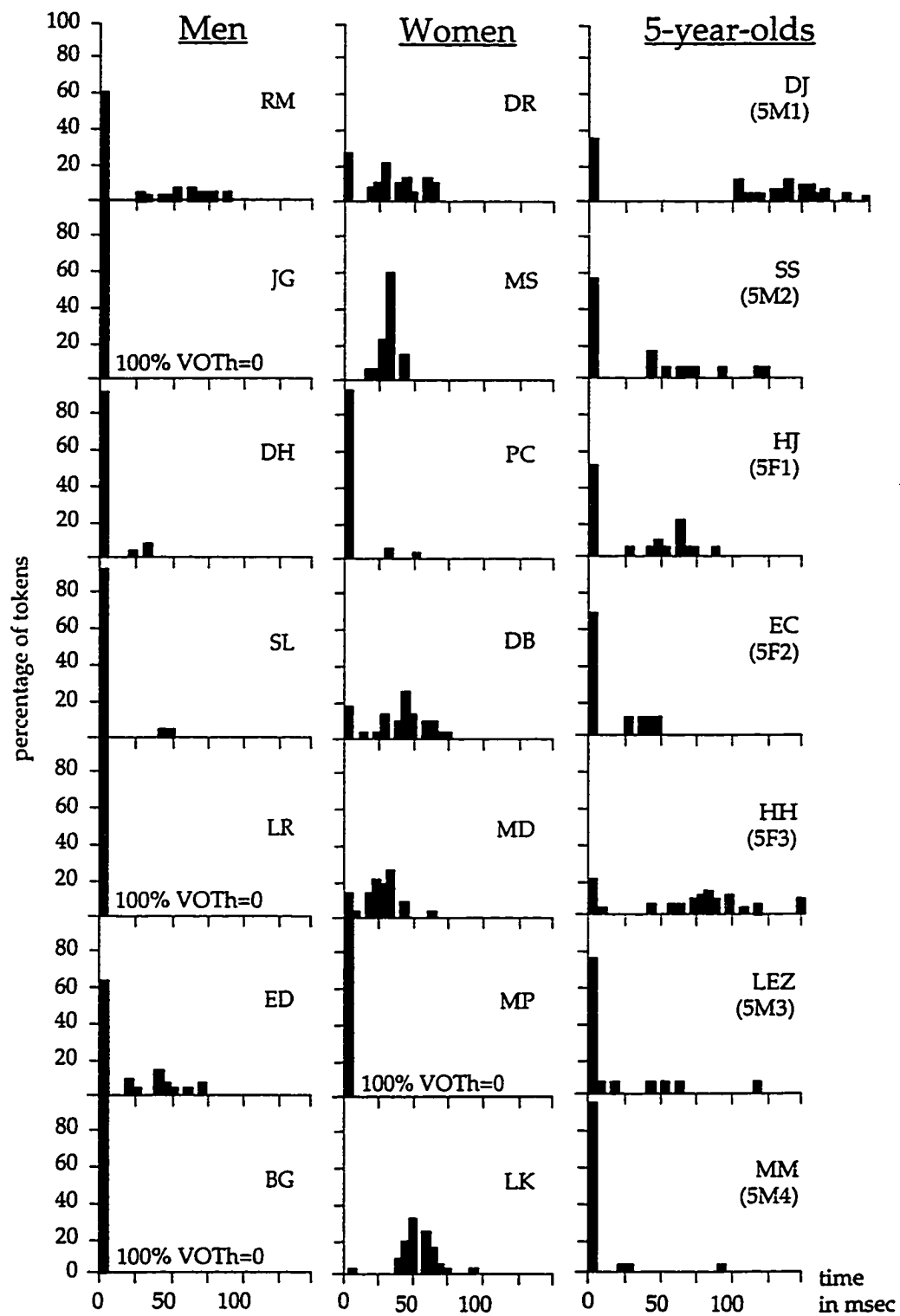
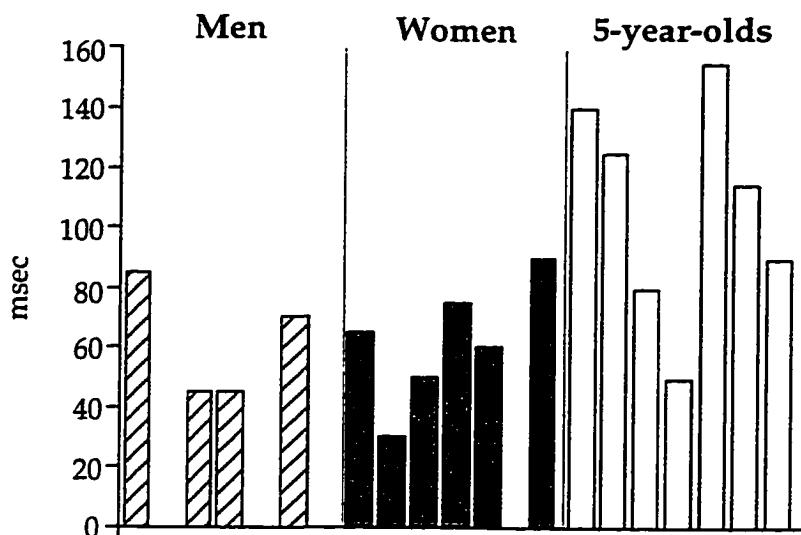
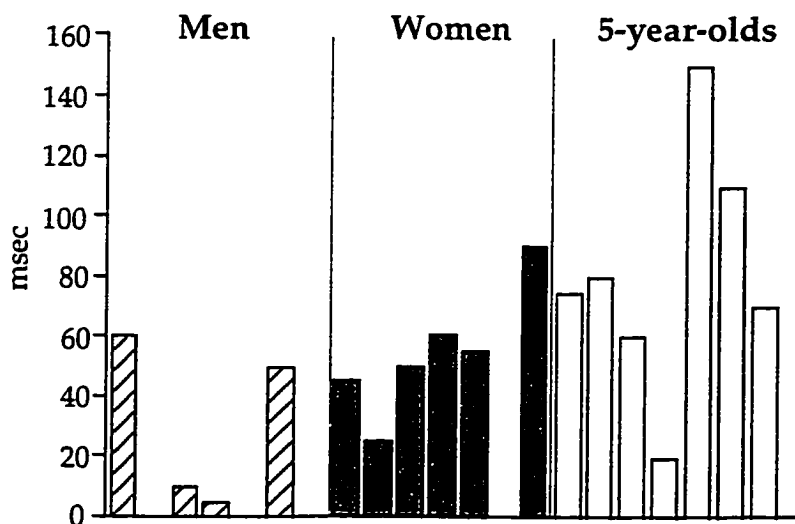
Figure 3.11: VOT_h, all subjects

Figure 3.12a: Subjects' ranges of VOTh: All tokens

Figure 3.12b: Subjects' ranges of VOTh:
Tokens where VOTh>0 only

Figures 3.12: Ranges of VOTh, all subjects.
Subjects are ordered numerically within groups

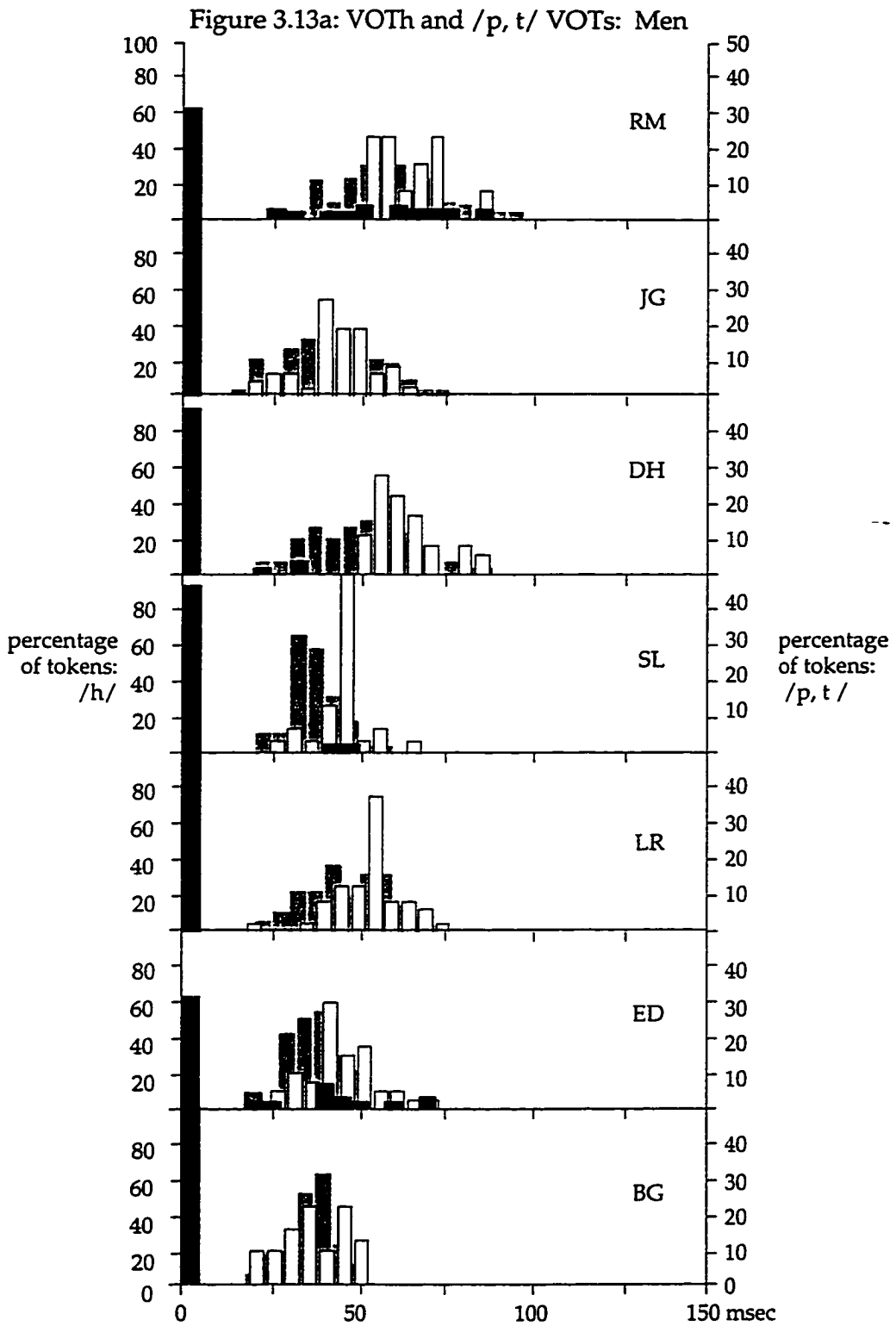


Figure 3.13.a: VOT_h and /p, t/ VOTs: Men

/h/= ■ /p/= ■ /t/= □

Figure 3.13b: VOTh and /p, t/ VOTs: Women

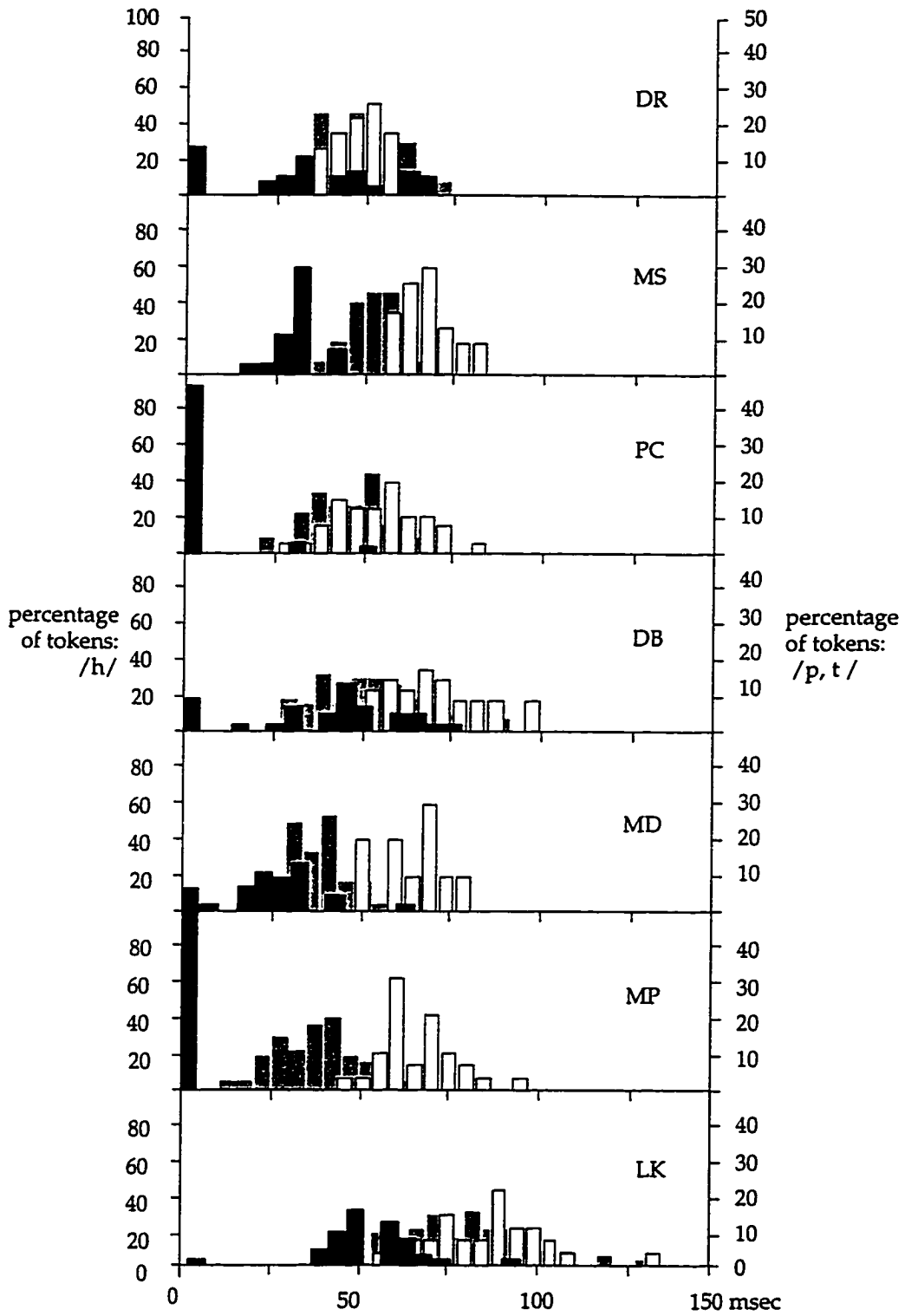


Figure 3.13b: VOTh and /p, t/ VOTs: Women

/h/ = ■ /p/ = ■ /t/ = □

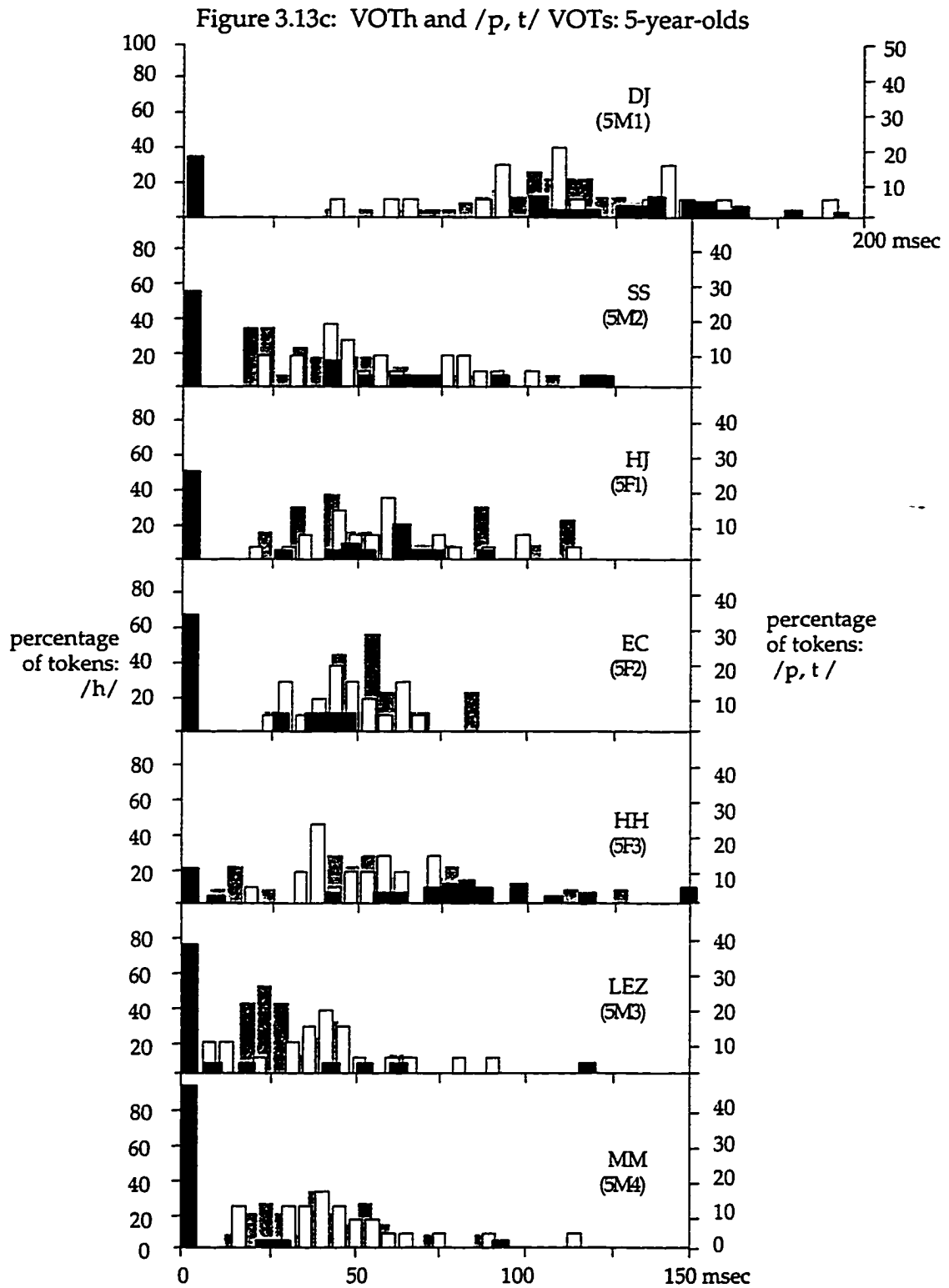


Figure 3.13c: VOTh and /p, t/ VOTs: 5-year-olds

/h/ = ■ /p/ = ■ /t/ = □

Maximum VOTs against maximum VOTh, within subjects
The x-axes are identical in the two plots

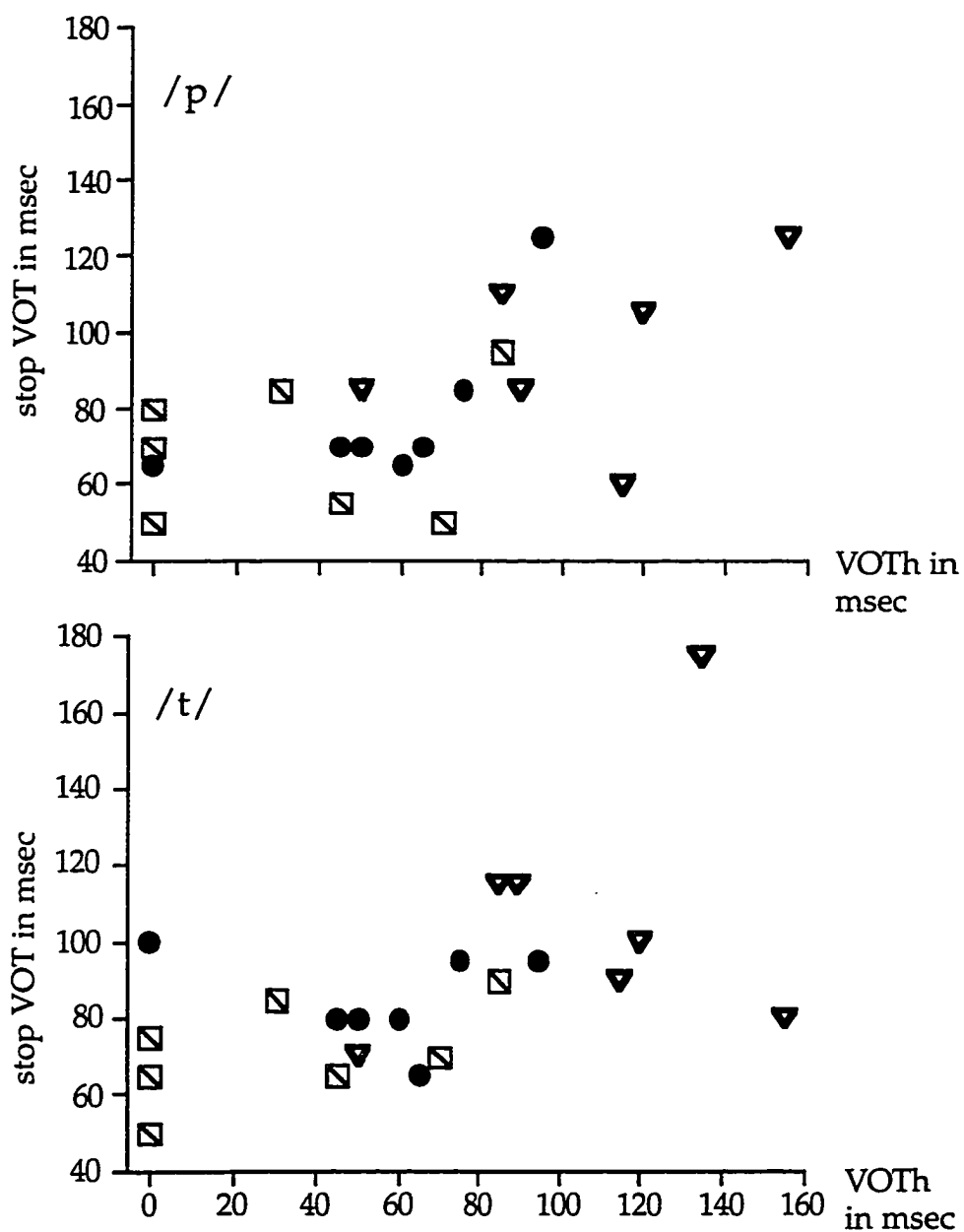


Figure 3.14: Maximum /p/ and /t/ VOTs against maximum VOTh within subjects

□ = Men, ● = Women, ▼ = 5-year-olds

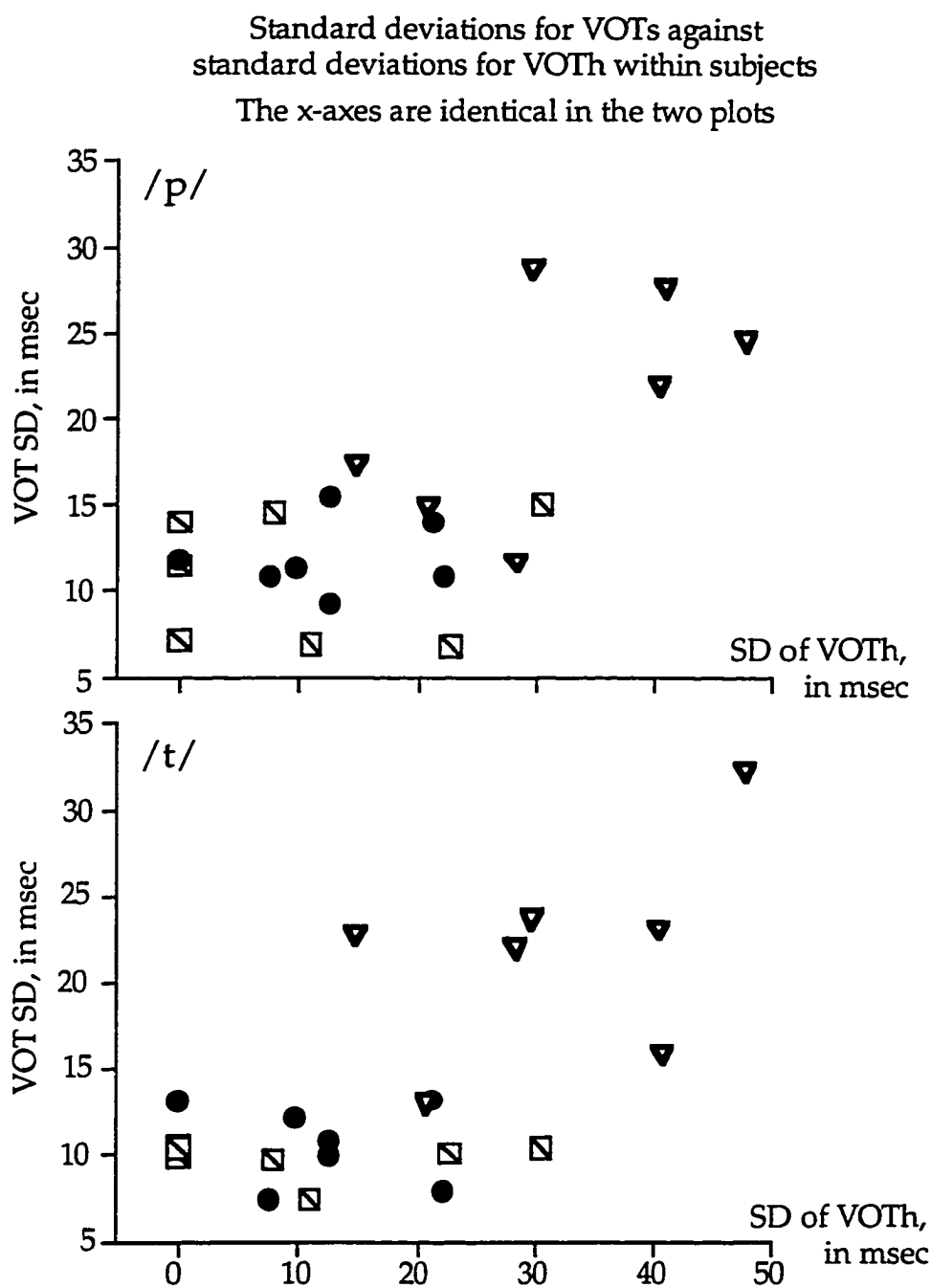


Figure 3.15: Standard deviations for /p/ and /t/ VOTs plotted against standard deviations for VOTh within subjects

□ = Men, ● = Women, ▼ = 5 year olds

Plots show regression lines for combined data when overall p-values reach or approach significance. \square = Men, \bullet = Women, \blacktriangledown = 5-year-olds. AF6-MP is shown unfilled. See text for discussion.

Figure 3.16a: % Voiced /h/ vs. height

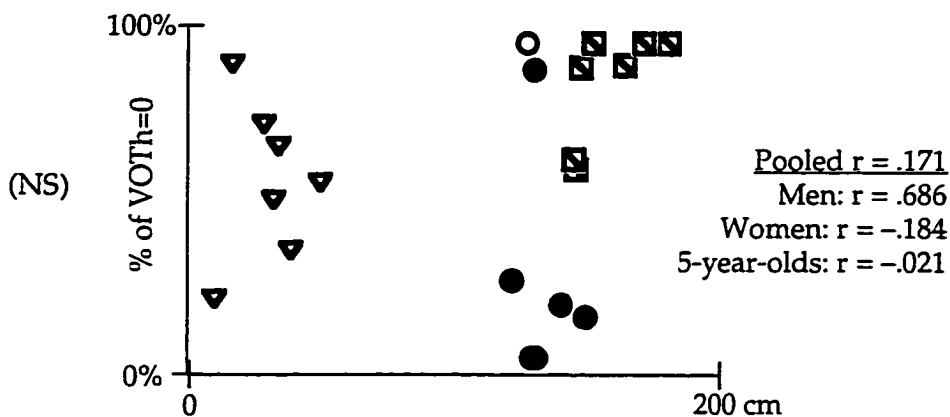
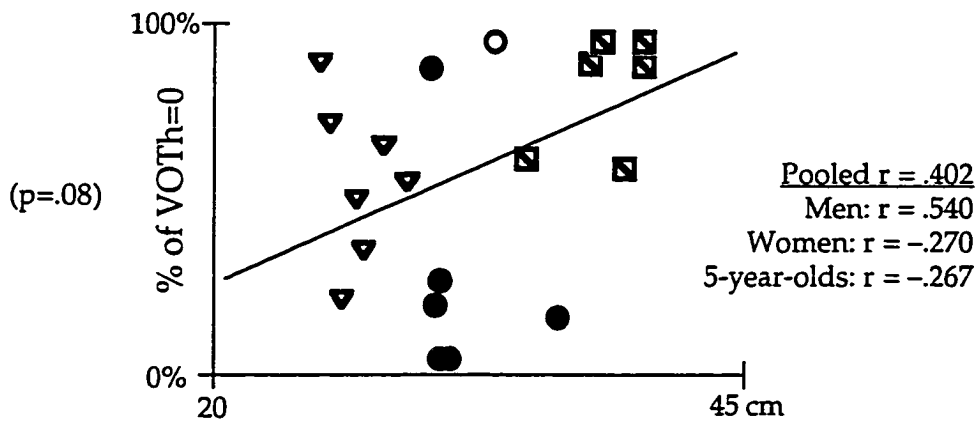
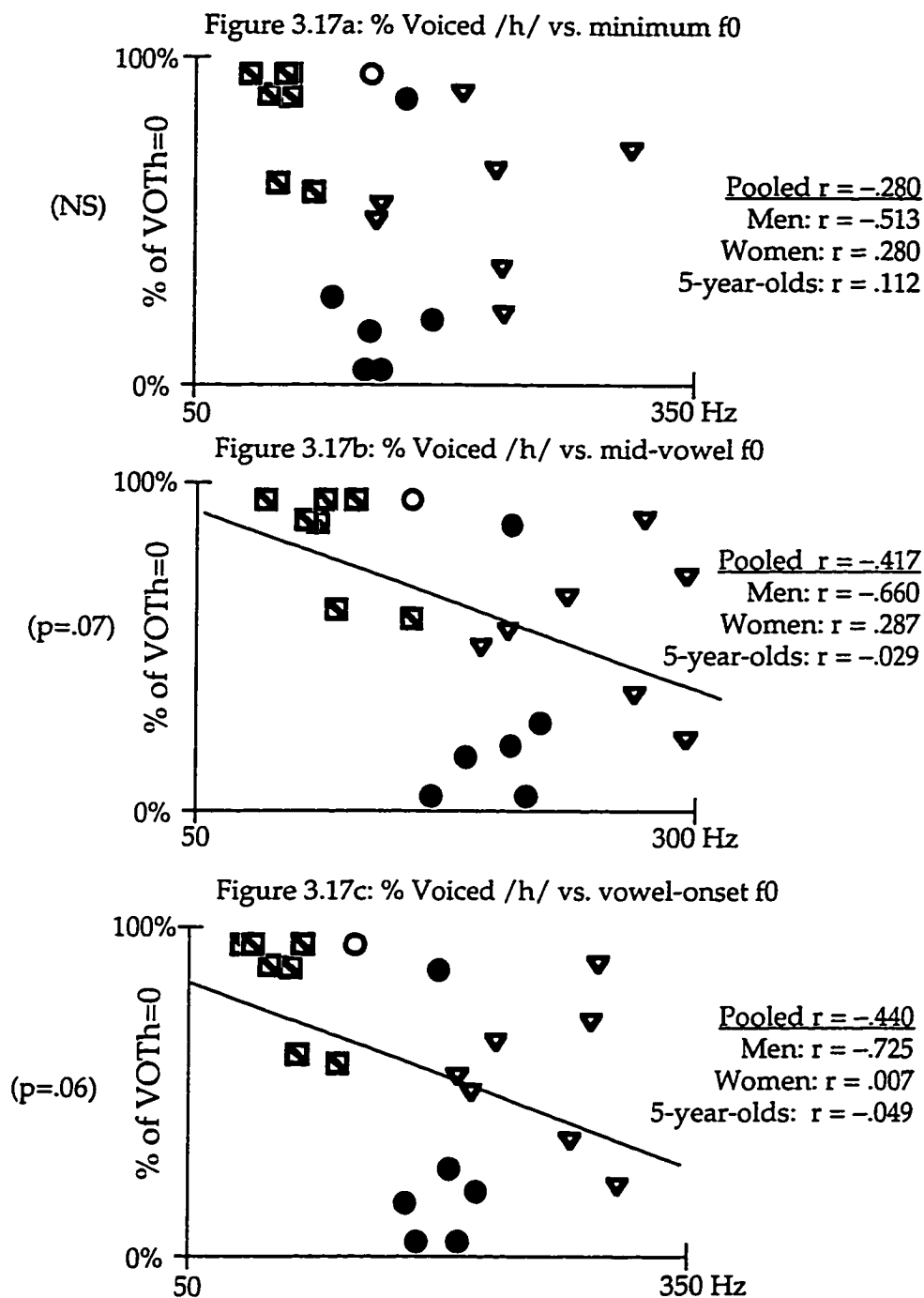


Figure 3.16b: % Voiced /h/ vs. neck circumference



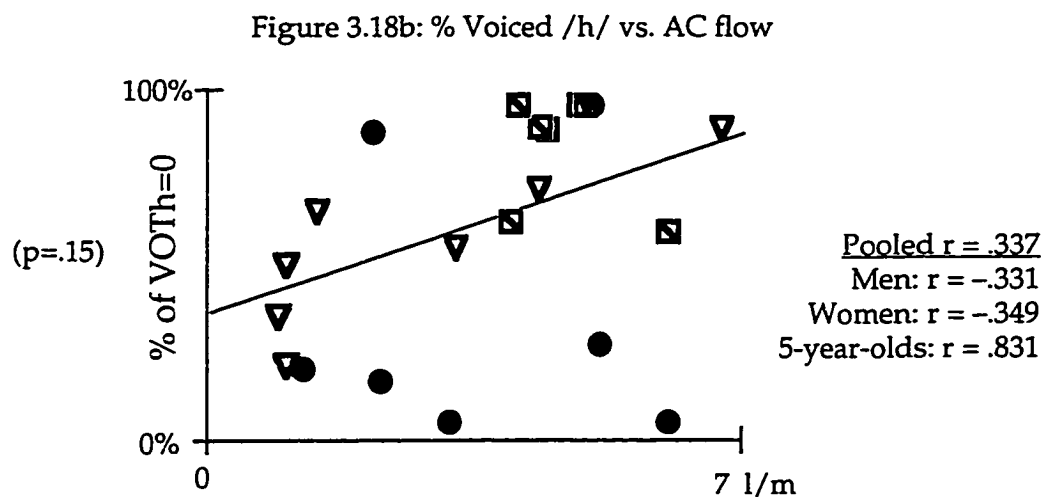
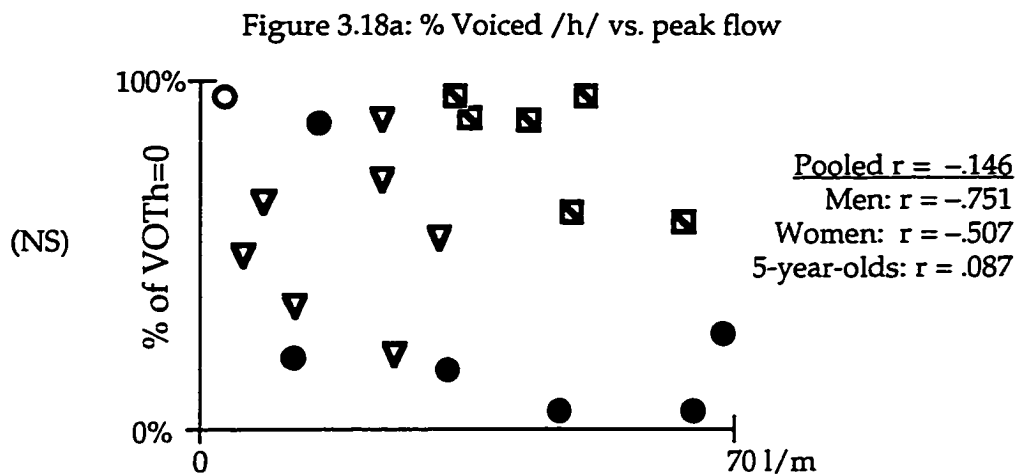
Figures 3.16: Percentage of fully voiced /h/ as a function of body size measures

Plots show regression lines for combined data when overall p-values reach or approach significance. \blacksquare = Men, \bullet = Women, \blacktriangledown = 5-year-olds. AF6-MP is shown unfilled. See text for discussion.



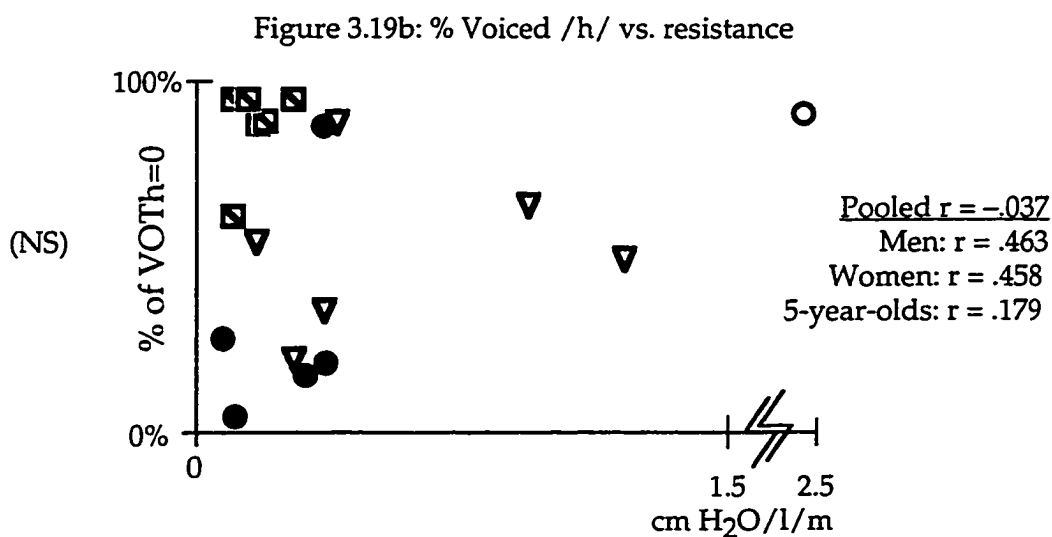
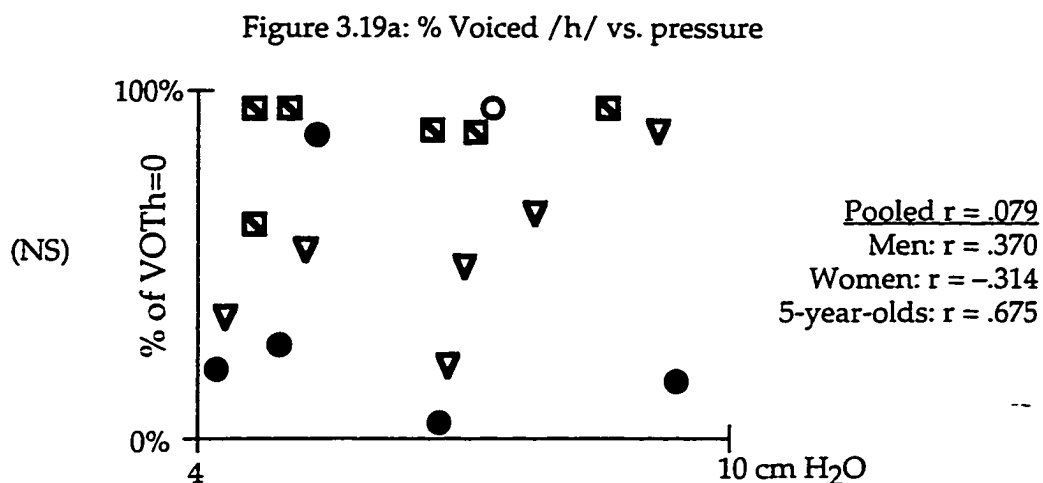
Figures 3.17: Percentage of fully voiced /h/ as a function of f_0 measures

Plots show regression lines for combined data when overall p-values reach or approach significance. \square = Men, \bullet = Women, \blacktriangledown = 5-year-olds. AF6-MP is shown unfilled. See text for discussion.

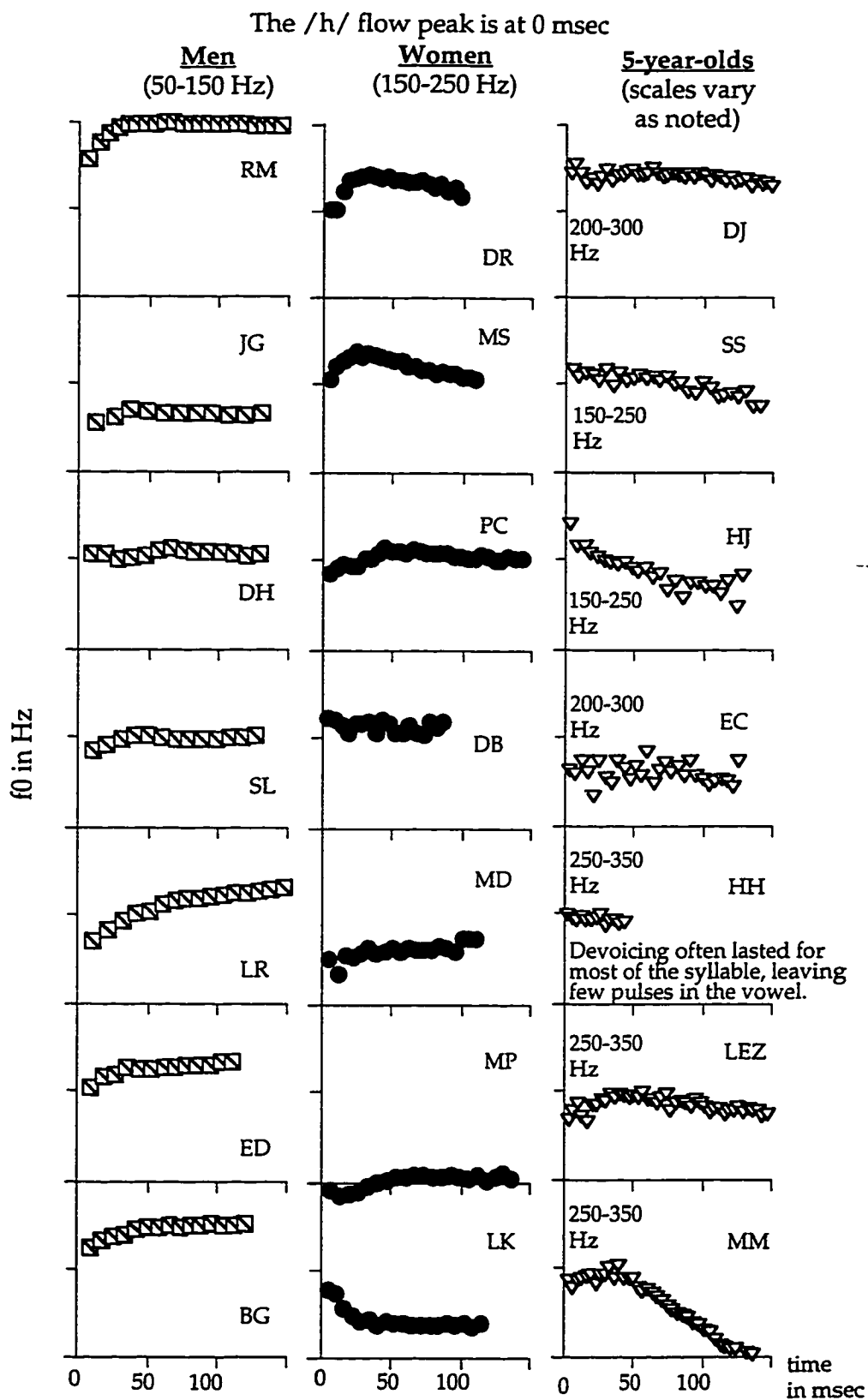


Figures 3.18: Percentage of fully voiced /h/ as a function of airflow measures

Plots show regression lines for combined data when overall p-values reach or approach significance. \square = Men, \bullet = Women, \blacktriangledown = 5-year-olds. AF6-MP is shown unfilled. See text for discussion.



Figures 3.19: Percentage of fully voiced /h/ as a function of pressure and resistance



All subjects on a scale of 0-20 l/m
 The /h/ flow peak is at 0 msec

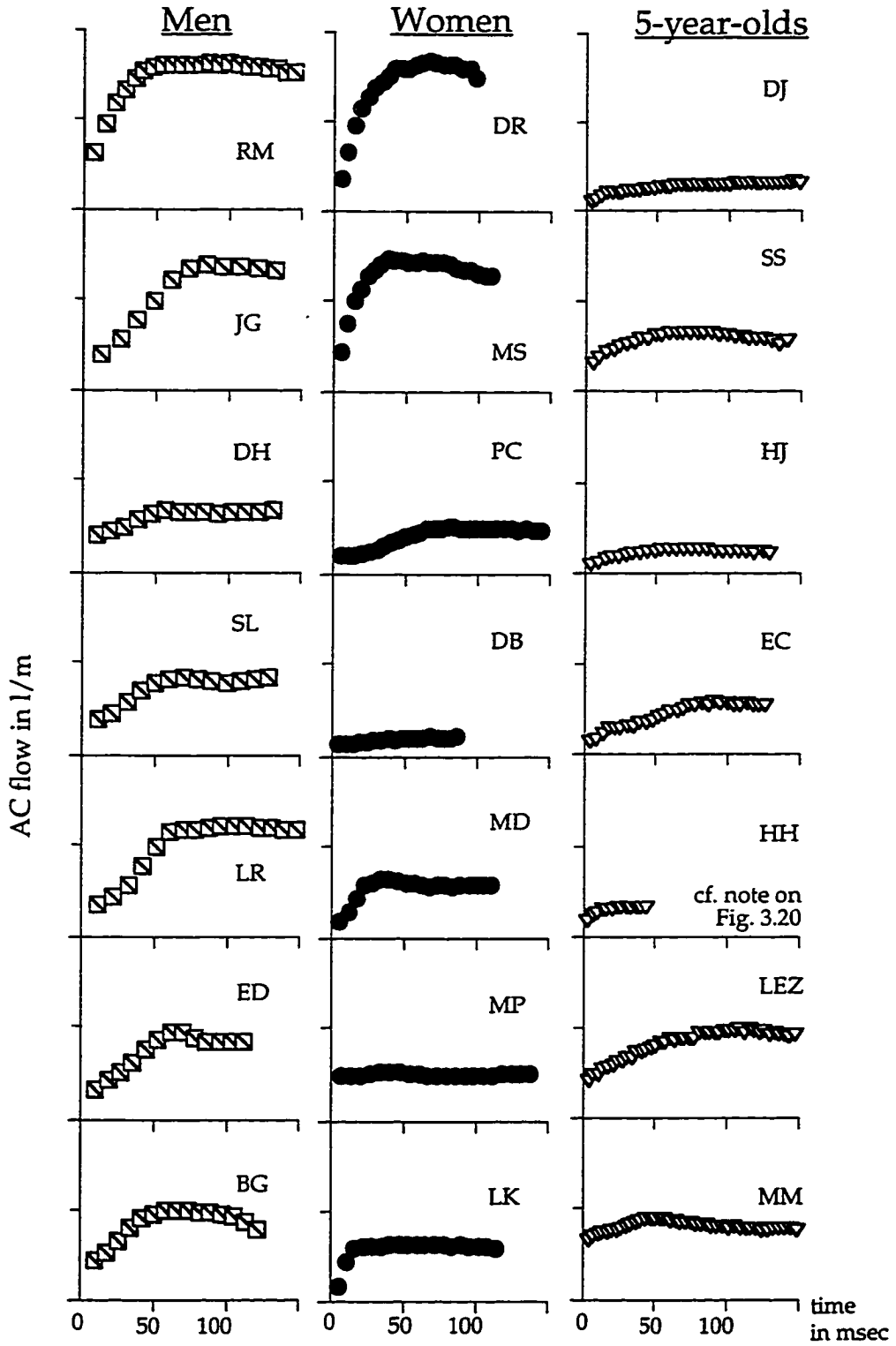


Figure 3.21: Average AC flow traces during /ha/

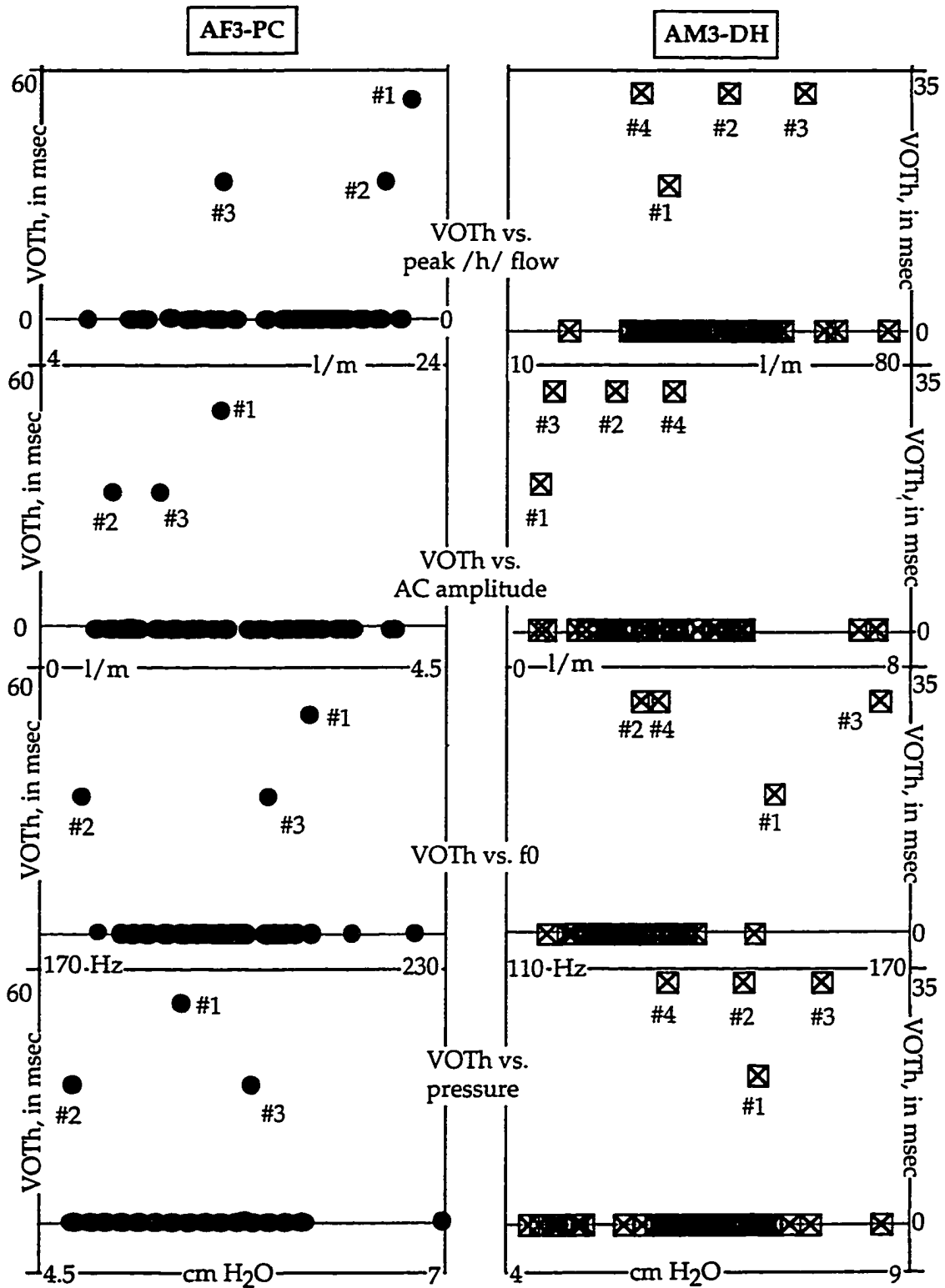


Figure 3.22: VOTh plotted against other measured variables for 2 subjects with mostly VOTh=0. See also Table 3.14

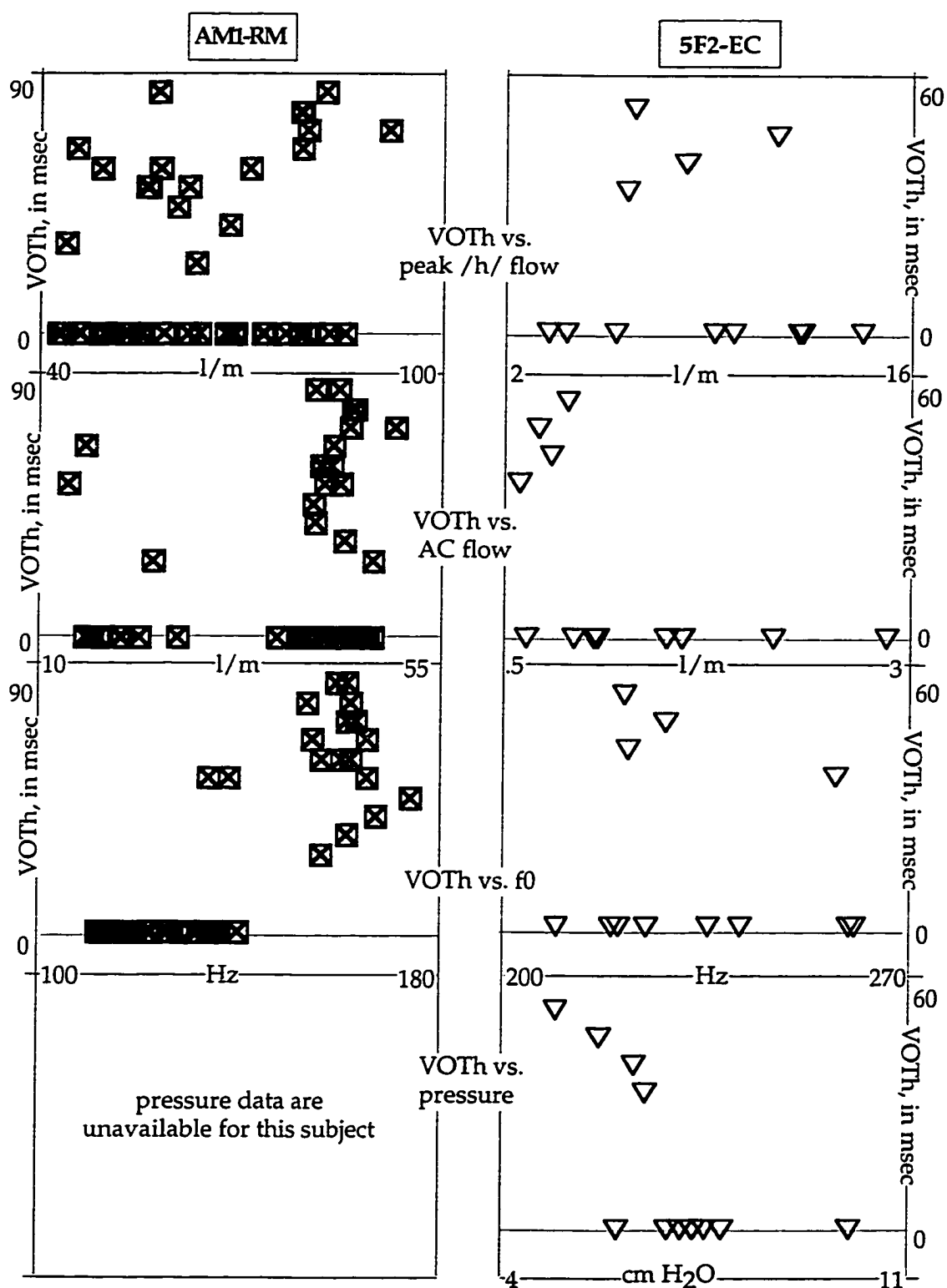


Figure 3.23: VOTh plotted against other measured variables for 2 subjects with a little more than 50% VOTh=0. See also Table 3.14

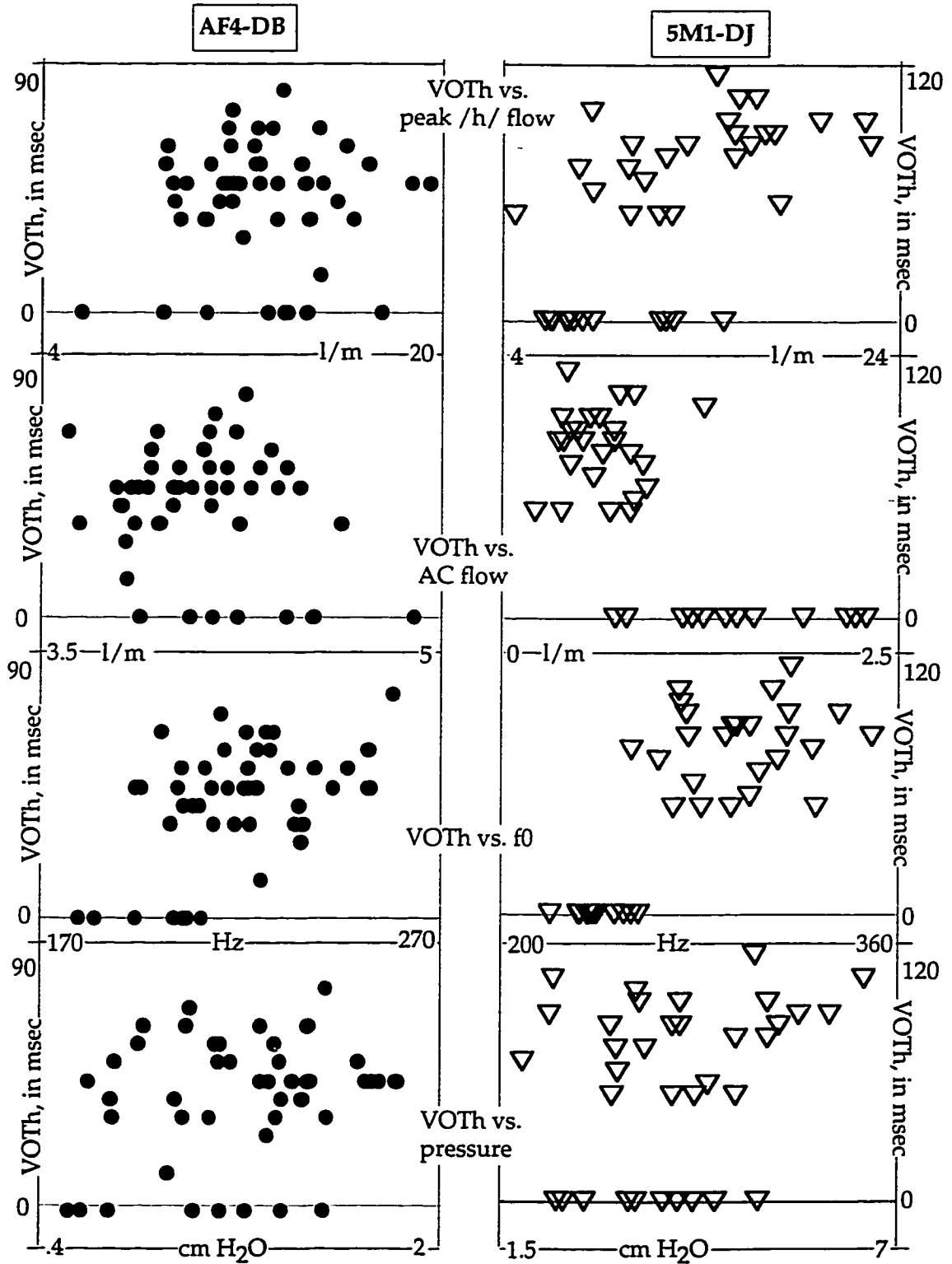


Figure 3.24: VOTh plotted against other measured variables for 2 subjects with mostly VOTh>0. See also Table 3.16

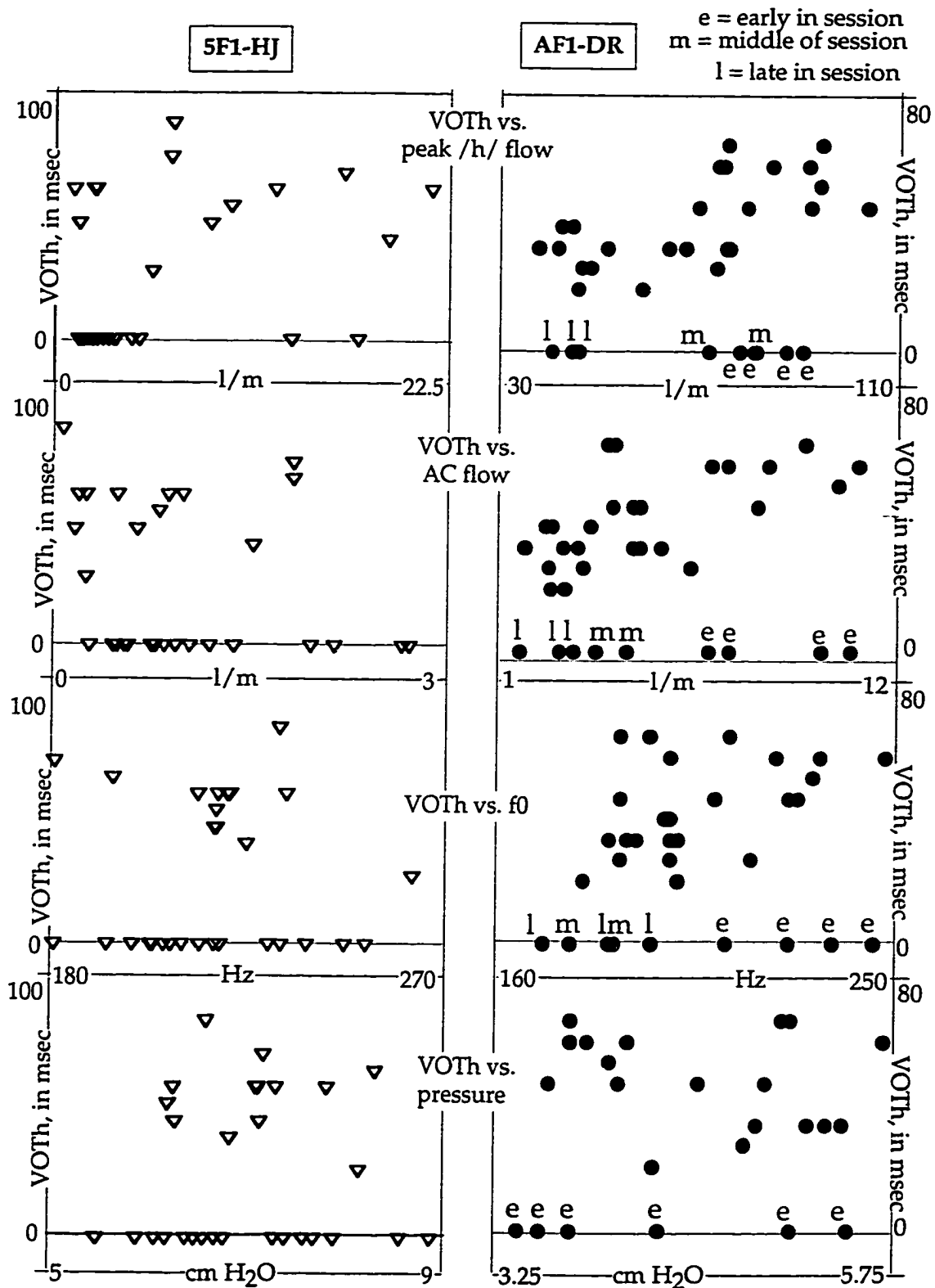


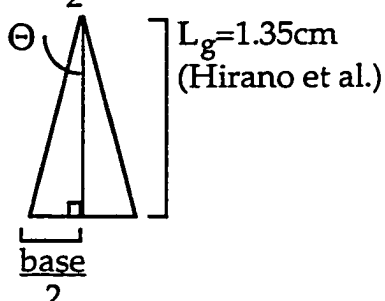
Figure 3.25: VOTh plotted against other measured variables for 2 subjects with mixed VOTh distributions. See also Tables 3.16-17

Appendix A: Estimation of glottal areas

Direct data on glottal cross-sectional areas are not available for children, and are usually estimated in adults. Aerodynamic simulations intended to mimic the output of an adult female (see McGowan et al. 1995) suggest that reasonable values for glottal areas in women are approximately .03 cm² under adducted conditions, and .3 cm² under abducted conditions. Using this, we can obtain a rough estimate for children, assuming a triangular glottis and a comparable degree of abduction (measured as an angle from midline), using the vocal fold length data given in Hirano et al. (1983) for adults and children.

Calculating the angle from midline under adducted (add) and abducted (abd) glottal conditions in women:

$$\text{Area} = \frac{1}{2} * \text{base} * \text{height}$$



$$.3 \text{ cm}^2 = 1.35 \text{ cm} (.5 * \text{base})$$

$$\Rightarrow (.5 * \text{base}) = .22 \text{ cm, abd.}$$

$$.03 \text{ cm}^2 = 1.35 \text{ cm} (.5 * \text{base})$$

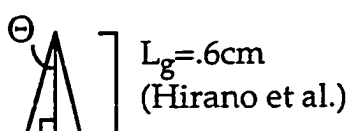
$$\Rightarrow (.5 * \text{base}) = .022 \text{ cm, add.}$$

Then the angles from midline are:

$$\tan \Theta_{\text{abd}} = (.22 \text{ cm} / 1.35 \text{ cm}) \Rightarrow \Theta_{\text{abd}} = 9.3^\circ$$

$$\tan \Theta_{\text{add}} = (.022 \text{ cm} / 1.35 \text{ cm}) \Rightarrow \Theta_{\text{add}} = .93^\circ$$

Now, assuming comparable angles of ad/abduction in the two groups, we have



$$\tan \Theta_{\text{abd}} = (.5 * \text{base}) / .6 \text{ cm}$$

$$\Rightarrow (.5 * \text{base}) = .0978 \text{ cm, abd.}$$

$$\tan \Theta_{\text{add}} = (.5 * \text{base}) / .6 \text{ cm}$$

$$\Rightarrow (.5 * \text{base}) = .00978 \text{ cm, add.}$$

and

$$\text{area} = .0978 \text{ cm} * .6 \text{ cm} = .059 \text{ cm}^2, \text{abd};$$

$$\text{area} = .0098 \text{ cm} * .6 \text{ cm} = .0059 \text{ cm}^2, \text{add.}$$

So the glottal area estimates (in cm²) are

	<u>abd</u>	<u>add</u>
women	.3	.03
5-year-olds	.059	.0059

with an area ratio between women and children of approximately 5.

Appendix B: Copies of subject consent forms

January 5, 1996

AIRFLOW MEASUREMENT - CHILD

HASKINS LABORATORIES
270 Crown Street, New Haven, Connecticut 06511

Consent to Act as a Research Subject

Project: Dynamics of Speech Articulation; grant DC-00121.

Your child is invited to participate in a speech production study involving the use of a screen-vented airflow measurement mask. You are, of course, free to decline, if you wish. Your child has been chosen because his/her speech production skills are of interest to the investigators.

During the experiment, the child will be asked to hold the mask up to his/her face, covering the mouth and nose. Alternatively, we may hold the mask for the child. S/he will be asked to say a series of short nonsense utterances through the mask's vented front. At the same time, we will make an acoustic recording of the child's voice. While the mask is in place, the child will continue to breathe room air, and air will be able to flow in and out of the child's mouth without difficulty.

There are no known risks of physical or psychological damage associated with the procedure. It will not impair your child's breathing, nor cause any bodily discomfort, aside from the novelty of speaking through the mask. This judgment is based on a large body of general knowledge about the effects of using masks of this type with both children and adults. Further, no personal information gathered in this study will be disclosed to any persons other than the investigators and their collaborators unless it is rendered anonymous.

This study will provide no direct benefit to you or your child, but will provide us with information that may lead to the future benefit of others.

The experimental procedure will entail a session of one to two hours with your child. At the end of the experiment, s/he will receive a prize for completing the procedure. You may accompany your child during the entire recording session. The experience should be a pleasant and interesting one for both you and your child. Of course, you may withdraw from the experiment at any time. Please feel free to ask about anything you don't understand and to consider this consent form carefully—as long as you feel is necessary—before you agree to your child's participation.

Authorization: I have read this form and decided that my son/daughter _____ will participate in the project described above. My signature also indicates that I have received a copy of this consent form.

Signature: _____

Relationship: _____

Date: _____

Appendix B: Copies of subject consent forms

Signature of Principal Investigator

Phone

Signature of Person Obtaining Consent

Phone

If you have further questions about this project or your child's rights as a research subject or if your child has a research-related injury, please contact the principal investigator, Vincent Gracco, telephone (203) 865-6163.

THIS FORM IS NOT VALID UNLESS THE FOLLOWING BOX HAS BEEN COMPLETED IN THE HIC OFFICE.

THIS FORM IS VALID ONLY UNTIL _____ (date)

HIC PROTOCOL NO. _____

INITIALED: _____

Appendix B: Copies of subject consent forms

January 5, 1996

INTRA-ORAL AIR PRESSURE - CHILD

HASKINS LABORATORIES
270 Crown Street, New Haven, Connecticut 06511

Consent to Act as a Research Subject

Project: Dynamics of Speech Articulation; grant DC-00121.

Your child is invited to participate in a speech production study involving the use of an oral pressure-sensing device. You are, of course, free to decline, if you wish. Your child has been chosen because his/her speech production skills are of interest to the investigators.

The procedure will involve positioning a thin flexible tube in the child's mouth during recording. The tube will pass through the side of the airflow mask to rest between the child's lips as s/he says a short series of nonsense utterances. The tube is connected to a device outside the mask which records changes in the air pressure inside the tube.—

There are no known risks of psychological damage associated with the procedure. Every proper precaution will be taken to sterilize the tube, so the risk of infection will be negligibly small. It will not cause any bodily discomfort, aside from the novelty of speaking with the tube in place. This judgment is based on a large body of general knowledge about the effects of using devices of this type with both children and adults. Further, no personal information gathered in this study will be disclosed to any persons other than the investigators and their collaborators unless it is rendered anonymous.

This study will provide no direct benefit to you or your child, but will provide us with information that may lead to the future benefit of others.

The experimental procedure will require approximately 20-30 minutes, and will be done only in conjunction with the Rothenberg mask procedure. You may accompany your child during the entire recording session. The experience should be a pleasant and interesting one for both you and your child. Of course, you may withdraw from the experiment at any time. Please feel free to ask about anything you don't understand and to consider this consent form carefully—as long as you feel is necessary—before you agree to your child's participation.

Authorization: I have read this form and decided that my son/daughter _____ will participate in the project described above. My signature also indicates that I have received a copy of this consent form.

Signature: _____

Relationship: _____

Date: _____

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Signature of Principal Investigator

Phone

Signature of Person Obtaining Consent

Phone

If you have further questions about this project or your child's rights as a research subject or if your child has a research-related injury, please contact the principal investigator, Vincent Gracco, telephone (203) 865-6163.

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THIS FORM IS VALID ONLY UNTIL _____ (date)

HIC PROTOCOL NO. _____

INITIALED: _____

Appendix B: Copies of subject consent forms

January 5, 1996

ACOUSTIC RECORDING - CHILD

HASKINS LABORATORIES
270 Crown Street, New Haven, Connecticut 06511

Consent to Act as a Research Subject

Project: Dynamics of Speech Articulation; grant DC-00121.

Your child is invited to participate in a speech production study. You are, of course, free to decline, if you wish. Your child has been chosen because his/her speech production skills are of interest to the investigators.

The study will involve making audio recordings of your child's voice as s/he produces a series of short nonsense utterances.

There are no known risks of physical or psychological damage associated with participation. This judgment is based on a large body of experience with similar studies involving children. Further, no personal information gathered in this study will be disclosed to any persons other than the investigators and their collaborators unless it is rendered anonymous.

This study will provide no direct benefit to you or your child, but will provide us with information that may lead to the future benefit of others.

The experimental procedure will entail a session of approximately 30 minutes with your child. At the end of the experiment, s/he will receive a prize for completing the procedure. You may accompany your child during the entire recording session. The experience should be a pleasant and interesting one for both you and your child. Of course, you may withdraw from the experiment at any time. Please feel free to ask about anything you don't understand and to consider this consent form carefully—as long as you feel is necessary—before you agree to your child's participation.

Authorization: I have read this form and decided that my son/daughter _____ will participate in the project described above. My signature also indicates that I have received a copy of this consent form.

Signature: _____

Relationship: _____

Date: _____

Signature of Principal Investigator

Phone

Signature of Person Obtaining Consent

Phone

Appendix B: Copies of subject consent forms

If you have further questions about this project or your child's rights as a research subject or if your child has a research-related injury, please contact the principal investigator, Vincent Gracco, telephone (203) 865-6163.

THIS FORM IS NOT VALID UNLESS THE FOLLOWING BOX HAS BEEN COMPLETED IN THE HIC OFFICE.

THIS FORM IS VALID ONLY UNTIL _____ (date)

HIC PROTOCOL NO. _____

INITIALED: _____

Appendix B: Copies of subject consent forms

January 5, 1996

AIRFLOW MEASUREMENT

HASKINS LABORATORIES
270 Crown Street, New Haven, Connecticut 06511

Consent to Act as a Research Subject

Project: Dynamics of Speech Articulation; grant DC-00121.

You are invited to participate in a speech production study involving the use of a screen-vented airflow measurement mask. You are, of course, free to decline, if you wish. You have been chosen because your speech production skills are of interest to the investigators.

During the experiment, you will be asked to hold the mask up to your face, covering the mouth and nose, while you produce a series of short nonsense utterances through the mask's vented front. At the same time, we will make an acoustic recording of your voice. While the mask is in place, you will continue to breathe room air, and air will be able to flow in and out of the mouth without difficulty. --

There are no known risks of physical or psychological damage associated with the procedure. It will not impair breathing, nor cause any bodily discomfort, aside from the novelty of speaking through the mask. This judgment is based on a large body of general knowledge about the effects of using masks of this type. Further, no personal information gathered in this study will be disclosed to any persons other than the investigators and their collaborators unless it is rendered anonymous.

This study will provide no direct benefit to you, but will provide us with information that may lead to the future benefit of others.

The experimental procedure will entail a session of approximately 30 minutes. Of course, you may withdraw from the experiment at any time. Please feel free to ask about anything you don't understand and to consider this consent form carefully—as long as you feel is necessary—before you agree to participate. However, we would like to defer answering questions that may influence your performance in the study until you have completed your participation.

Authorization: I have read this form and decided that _____ will participate in the project described above. My signature also indicates that I have received a copy of this consent form.

Signature: _____

Relationship: _____

Date: _____

Appendix B: Copies of subject consent forms

Signature of Principal Investigator

Phone

Signature of Person Obtaining Consent

Phone

If you have further questions about this project or your rights as a research subject or if you have a research-related injury, please contact the principal investigator, Vincent Gracco, telephone (203) 865-6163.

THIS FORM IS NOT VALID UNLESS THE FOLLOWING BOX HAS BEEN COMPLETED IN THE HIC OFFICE.

THIS FORM IS VALID ONLY UNTIL _____ (date)

HIC PROTOCOL NO. _____

INITIALED: _____

Appendix B: Copies of subject consent forms

January 5, 1996

INTRA-ORAL AIR PRESSURE

HASKINS LABORATORIES
270 Crown Street, New Haven, Connecticut 06511

Consent to Act as a Research Subject

Project: Dynamics of Speech Articulation; grant DC-00121.

You are invited to participate in a speech production study involving the use of a oral pressure-sensing device. You are, of course, free to decline, if you wish. You have been chosen because your speech production skills are of interest to the investigators.

The procedure will involve positioning a thin flexible tube in your mouth during recording. The tube will pass through the side of the airflow mask to rest between the lips while you say a short series of nonsense utterances. The tube is connected to a device outside the mask which records changes in the air pressure inside the tube.

There are no known risks of psychological damage associated with the procedure. Every proper precaution will be taken to sterilize the tube, so the risk of infection will be negligibly small. It will not cause any bodily discomfort, aside from the novelty of speaking with the tube in place. This judgment is based on a large body of general knowledge about the effects of using devices of this type. Further, no personal information gathered in this study will be disclosed to any persons other than the investigators and their collaborators unless it is rendered anonymous.

This study will provide no direct benefit to you, but will provide us with information that may lead to the future benefit of others.

The experimental procedure will require approximately 10-15 minutes, and will be done only in conjunction with the Rothenberg mask procedure. Of course, you are free to withdraw from the experiment at any time. Please feel free to ask about anything you don't understand and to consider this consent form carefully—as long as you feel is necessary—before you agree to participate. However, we would like to defer answering questions that may influence your performance in the study until you have completed your participation.

Authorization: I have read this form and decided that _____ will participate in the project described above. My signature also indicates that I have received a copy of this consent form.

Signature: _____

Relationship: _____

Date: _____

Appendix B: Copies of subject consent forms

Signature of Principal Investigator

Phone

Signature of Person Obtaining Consent

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If you have further questions about this project or your rights as a research subject or if you have a research-related injury, please contact the principal investigator, Vincent Gracco, telephone (203) 865-6163.

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THIS FORM IS VALID ONLY UNTIL _____ (date)

HIC PROTOCOL NO. _____

INITIALED: _____

Appendix C: Results of Mann-Whitney U-tests for voicing category

Mann-Whitney U test results		Mann-Whitney Rank info.		Mann-Whitney U test results		Mann-Whitney Rank info.			
AM1-RM /p-b/	U U Prime Z-Value P-Value Tied Z-Value Tied P-Value # Ties	0 3127 -9.111 <.0001 -9.111 <.0001 1	Count Ranks Sum Mean Rank	59 1770 30	AM3-DH /p-b/	U U Prime Z-Value P-Value Tied Z-Value Tied P-Value # Ties	0 1440 -7.129 <.0001 -7.129 <.0001 0	Count Ranks Sum Mean Rank	24 300 12.5 54.5
/t-d/	U U Prime Z-Value P-Value Tied Z-Value Tied P-Value # Ties	0 156 -4.243 <.0001 -4.243 <.0001 0	Count Ranks Sum Mean Rank	12 78 6.5 19	/t-d/	U U Prime Z-Value P-Value Tied Z-Value Tied P-Value # Ties	0 432 -5.143 <.0001 -5.143 <.0001 0	Count Ranks Sum Mean Rank	12 78 6.5 30.5
AM2-JG /p-b/	U U Prime Z-Value P-Value Tied Z-Value Tied P-Value # Ties	4 2410 -8.238 <.0001 -8.238 <.0001 0	Count Ranks Sum Mean Rank	34 599 17.618 69.944	AM4-SL /p-b/	U U Prime Z-Value P-Value Tied Z-Value Tied P-Value # Ties	0 870 -5.939 <.0001 -5.939 <.0001 0	Count Ranks Sum Mean Rank	15 120 8 44.5
/t-d/	U U Prime Z-Value P-Value Tied Z-Value Tied P-Value # Ties	0 1152 -6.881 <.0001 -6.881 <.0001 0	Count Ranks Sum Mean Rank	24 300 12.5 48.5	/t-d/	U U Prime Z-Value P-Value Tied Z-Value Tied P-Value # Ties	0 450 -5.417 <.0001 -5.417 <.0001 0	Count Ranks Sum Mean Rank	15 120 8 30.5

Appendix C: Results of Mann-Whitney U-tests for voicing category

Mann-Whitney U test results		Mann-Whitney Rank info.		Mann-Whitney U test results		Mann-Whitney Rank info.	
AM5-LR	U	0	Sum Ranks	AM7-BG	U	1	Sum Ranks
/p-b/	U Prime	1992	Count	/p-b/	U Prime	639	Count
	Z-Value	-7.439	vcd		Z-Value	-5.786	vcd
	P-Value	<.0001	vcls		P-Value	<.0001	vcls
	Tied Z-Value	-7.439			Tied Z-Value	-5.786	
	Tied P-Value	<.0001			Tied P-Value	<.0001	
	# Ties	0			# Ties	0	
/t-d/	U	0	Sum Ranks	/t-d/	U	2	Sum Ranks
	U Prime	1152	Count		U Prime	510	Count
	Z-Value	-6.881	vcd		Z-Value	-5.555	vcd
	P-Value	<.0001	vcls		P-Value	<.0001	vcls
	Tied Z-Value	-6.881			Tied Z-Value	-5.555	
	Tied P-Value	<.0001			Tied P-Value	<.0001	
	# Ties	0			# Ties	0	
AM6-ED	U	0	Sum Ranks		U	0	Sum Ranks
/p-b/	U Prime	960	Count		U Prime	360	Count
	Z-Value	-6.461	vcd		Z-Value	-4.648	vcd
	P-Value	<.0001	vcls		P-Value	<.0001	vcls
	Tied Z-Value	-6.461			Tied Z-Value	-4.648	
	Tied P-Value	<.0001			Tied P-Value	<.0001	
	# Ties	0			# Ties	0	
/t-d/	U	0	Sum Ranks		U	0	Sum Ranks
	U Prime	360	Count		U Prime	45	Count
	Z-Value	-4.648	vcd		Z-Value	-4.648	vcd
	P-Value	<.0001	vcls		P-Value	<.0001	vcls
	Tied Z-Value	-4.648			Tied Z-Value	-4.648	
	Tied P-Value	<.0001			Tied P-Value	<.0001	
	# Ties	0			# Ties	0	

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Appendix C: Results of Mann-Whitney U-tests for voicing category

Mann-Whitney U test results		Mann-Whitney Rank info.		Mann-Whitney U test results		Mann-Whitney Rank info.					
AF1-DR	/p-b/	U	0	Count	Sum	AF3-PC	/p-b/	U	39	Count	Sum
		U Prime	1296	vcd	666			U Prime	1226	vcd	315
		Z-Value	-7.298	vcls	1962			Z-Value	-6.504	vcls	2766
		P-Value	<.0001					P-Value	<.0001		
		Tied Z-Value	-7.298					Tied Z-Value	-6.504		
		Tied P-Value	<.0001					Tied P-Value	<.0001		
		# Ties	0					# Ties	0		
	/t-d/	U	0	Count <th>Sum</th> <td></td> <td></td> <td>U</td> <td>2</td> <td>Count <th>Sum</th> </td>	Sum			U	2	Count <th>Sum</th>	Sum
		U Prime	312	vcd	91			U Prime	982	vcd	302
		Z-Value	-4.963	vcls	612			Z-Value	-6.661	vcls	1843
		P-Value	<.0001					P-Value	<.0001		
		Tied Z-Value	-4.963					Tied Z-Value	-6.661		
		Tied P-Value	<.0001					Tied P-Value	<.0001		
		# Ties	0					# Ties	0		
Mann-Whitney U test results		Mann-Whitney Rank info.		Mann-Whitney U test results		Mann-Whitney Rank info.					
AF2-MS	/p-b/	U	0	Count	Sum	AF4-DB	/p-b/	U	22	Count	Sum
		U Prime	432	vcd	78			U Prime	1562	vcd	275
		Z-Value	-5.143	vcls	1098			Z-Value	-6.876	vcls	4190
		P-Value	<.0001					P-Value	<.0001		
		Tied Z-Value	-5.143					Tied Z-Value	-6.876		
		Tied P-Value	<.0001					Tied P-Value	<.0001		
		# Ties	0					# Ties	0		
	/t-d/	U	0	Count <th>Sum</th> <td></td> <td></td> <td>U</td> <td>0</td> <td>Count <th>Sum</th> </td>	Sum			U	0	Count <th>Sum</th>	Sum
		U Prime	288	vcd	78			U Prime	432	vcd	78
		Z-Value	-4.832	vcls	588			Z-Value	-5.143	vcls	1098
		P-Value	<.0001					P-Value	<.0001		
		Tied Z-Value	-4.832					Tied Z-Value	-5.143		
		Tied P-Value	<.0001					Tied P-Value	<.0001		
		# Ties	0					# Ties	0		

Appendix C: Results of Mann-Whitney U-tests for voicing category

Mann-Whitney U test results		Mann-Whitney Rank info.			Mann-Whitney U test results		Mann-Whitney Rank info.				
AF5-MD	/p-b/	U	1	Count	Sum	AF7-LK	/p-b/	U	0	Count	Sum
		Prime	Rank	Ranks	Mean			Prime	Rank	Ranks	Mean
		979	10.55	20	211			2133	14	27	378
		Z-Value		vcd				Z-Value		vcd	
		-6.468		49	2204			-7.733		79	5293
		P-Value		vcls				<.0001		vcls	
		<.0001						<.0001			
		Tied Z-Value						Tied Z-Value			
		-6.468						-7.733			
		Tied P-Value						<.0001			
		<.0001						<.0001			
		# Ties						# Ties			
		0						0			
	/t-d/	U	0	Count	Sum		/t-d/	U	0	Count	Sum
		Prime	Rank	Ranks	Mean			Prime	Rank	Ranks	Mean
		100	5.5	10	55			435	8	15	120
		Z-Value		vcd				Z-Value		vcd	
		-3.78		10	155			-5.385		29	870
		P-Value		vcls				<.0001		vcls	
		0.0002						<.0001			
		Tied Z-Value						Tied Z-Value			
		-3.78						-5.385			
		Tied P-Value						<.0001			
		0.0002						<.0001			
		# Ties						# Ties			
		0						0			
	AF6-MP	U	0	Count	Sum		AF6-MP	U	0	Count	Sum
	/p-b/	Prime	Rank	Ranks	Mean			Prime	Rank	Ranks	Mean
		1083	10	19	190			812	14.5	28	406
		Z-Value		vcd				Z-Value		vcd	
		-6.496		57	2736			-6.481		29	1247
		P-Value		vcls				<.0001		vcls	
		<.0001						<.0001			
		Tied Z-Value						Tied Z-Value			
		-6.496						-6.481			
		Tied P-Value						<.0001			
		<.0001						<.0001			
		# Ties						# Ties			
		0						0			
	/t-d/	U	0	Count	Sum		/t-d/	U	0	Count	Sum
		Prime	Rank	Ranks	Mean			Prime	Rank	Ranks	Mean
		812	14.5	28	406			812	14.5	28	406
		Z-Value		vcd				Z-Value		vcd	
		-6.481		29	1247			-6.481		29	1247
		P-Value		vcls				<.0001		vcls	
		<.0001						<.0001			
		Tied Z-Value						Tied Z-Value			
		-6.481						-6.481			
		Tied P-Value						<.0001			
		<.0001						<.0001			
		# Ties						# Ties			
		0						0			

Appendix C: Results of Mann-Whitney U-tests for voicing category

Mann-Whitney U test results		Mann-Whitney Rank info.		Mann-Whitney U test results		Mann-Whitney Rank info.	
5M1-D) /p-b/	U U Prime Z-Value P-Value Tied Z-Value Tied P-Value # Ties	1 659 -5.38 <.0001 -5.38 <.0001 0	Sum Mean Count Ranks Rank 12 79 6.583 55 2199 39.982	5F1-HJ /p-b/	U U Prime Z-Value P-Value Tied Z-Value Tied P-Value # Ties	6 318 -4.747 <.0001 -4.747 <.0001 0	Sum Mean Count Ranks Rank 12 84 7 27 696 25.78
/t-d/	U U Prime Z-Value P-Value Tied Z-Value Tied P-Value # Ties	0 200 -4.399 <.0001 -4.399 <.0001 0	Sum Mean Count Ranks Rank 10 55 5.5 20 410 20.5	/t-d/	U U Prime Z-Value P-Value Tied Z-Value Tied P-Value # Ties	2 286 -4.765 <.0001 -4.765 <.0001 0	Sum Mean Count Ranks Rank 12 80 6.667 24 586 24.42
5M2-SS /p-b/	U U Prime Z-Value P-Value Tied Z-Value Tied P-Value # Ties	37 323 -3.808 0.0001 -3.808 0.0001 0	Sum Mean Count Ranks Rank 10 92 9.2 36 989 27.472	5F2-EC /p-b/	U U Prime Z-Value P-Value Tied Z-Value Tied P-Value # Ties	0 90 -3.354 0.0008 -3.354 0.0008 0	Sum Mean Count Ranks Rank 5 15 3 18 261 14.5
/t-d/	U U Prime Z-Value P-Value Tied Z-Value Tied P-Value # Ties	4 238 -4.468 <.0001 -4.468 <.0001 0	Sum Mean Count Ranks Rank 11 70 6.364 22 491 22.318	/t-d/	U U Prime Z-Value P-Value Tied Z-Value Tied P-Value # Ties	1 146 -3.847 0.0001 -3.847 0.0001 0	Sum Mean Count Ranks Rank 7 29 4.143 21 377 17.95

Appendix C: Results of Mann-Whitney U-tests for voicing category

Mann-Whitney U test results		Mann-Whitney Rank info.			Mann-Whitney U test results		Mann-Whitney Rank info.		
5M3-LEZ	U	3	Count	Sum	5F3-HH	U	Count	Sum	Mean
/p-b/	U Prime	97	5	18	/p-b/	U Prime	13	113	8.692
	Z-Value	-3.193	vcd	3.6		Z-Value	vcd	113	8.692
	P-Value	0.0014	vcls	15.35		P-Value	vcls	30	833
	Tied Z-Value	-3.193				Tied Z-Value			
	Tied P-Value	0.0014				Tied P-Value			
	# Ties	0				# Ties			
/t-d/	U	20	Count	Sum	/t-d/	U	Count	Sum	Mean
	U Prime	156	8	56		U Prime	11	68	6.182
	Z-Value	-3.189	vcd	7		Z-Value	vcd	11	68
	P-Value	0.0014	vcls	18.591		P-Value	vcls	22	493
	Tied Z-Value	-3.189				Tied Z-Value			
	Tied P-Value	0.0014				Tied P-Value			
	# Ties	0				# Ties			

Mann-Whitney U test results		Mann-Whitney Rank info.			Mann-Whitney U test results		Mann-Whitney Rank info.		
5M4-MM	U	6	Count	Sum	5M4-MM	U	Count	Sum	Mean
/p-b/	U Prime	354	12	84	/p-b/	U Prime	15	120	8
	Z-Value	-4.845	vcd	7		Z-Value	vcd	15	120
	P-Value	<.0001	vcls	27.3		P-Value	vcls	25	700
	Tied Z-Value	-4.845				Tied Z-Value			
	Tied P-Value	<.0001				Tied P-Value			
	# Ties	0				# Ties			
/t-d/	U	0	Count	Sum	/t-d/	U	Count	Sum	Mean
	U Prime	375	15	120		U Prime	15	120	8
	Z-Value	-5.238	vcd	8		Z-Value	vcd	15	120
	P-Value	<.0001	vcls	28		P-Value	vcls	25	700
	Tied Z-Value	-5.238				Tied Z-Value			
	Tied P-Value	<.0001				Tied P-Value			
	# Ties	0				# Ties			

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Appendix D: Results of ANOVAs performed on selected measures

Summary of ANOVAs performed

	Meds	Means	SDs	CoVs	Skew	Skew/SE	Range	%=0
/b/ VOT	√	√	√		√			
/d/ VOT	√	√	√		√			
/p/ VOT	√	√	√	√	√	√		
/t/ VOT	√	√	√	√	√			
Vdur1 (unstr)	√	√	√	√				
Vdur2 (str)	√	√	√	√				
Pres.	√	√	√	√				
Pk /h/ flow	√	√	√	√				
VOT h	√		√				√	√

Means of VOTh were not computed given extreme non-normality of data. CoVs were not computed for /b, d/ VOTs, and VOTh because they sometimes had means close to 0 leading to very high or undefined values for CoV.

Skew was analyzed on stop VOTs only. Skew/SE was analyzed for the single case where the ANOVA for skew was significant. Range and %=0 were measured defined for VOTh only.

Summary of significant ANOVAs

** p<.01 * .01<p<.05 ~ .05<p<.10
showing post-hoc tests where p≤.05

	Meds	Means	SDs	CoVs	Skew	Skew/SE	Range	%=0
/b/ VOT								
/d/ VOT								
/p/ VOT			** 5>F 5>M	** 5>F 5>M	** 5>F 5>M	~ 5>M		
/t/ VOT			** 5>F 5>M	** 5>F 5>M				
Vdur1 (unstr)	** 5>F 5>M	** 5>F 5>M	** 5>F 5>M	* 5>F				
Vdur2 (str)			** 5>F 5>M	** 5>F 5>M				
Pres.			* 5>F	* 5>F				
Pk /h/ flow	~	* 5<M		* 5>M				
VOT h	~		** 5>F 5>M				all data ** 5>F 5>M	VOTh>0 ~ 5>M

Appendix D: ANOVA results

Median values: Results for all measures (see cover page)

/b/ medians. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	18.452	9.226	0.301	0.744
Resid.	18	551.786	30.655		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	7	12.5	6.292	2.378	
women	7	12.857	5.669	2.143	
men	7	10.714	4.499	1.7	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	-0.357	7.891	0.993		
5 yr olds, men	1.786	7.891	0.835		
women, men	2.143	7.891	0.772		

/d/ medians. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	25.595	12.798	0.668	0.525
Resid.	18	344.643	19.147		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	7	12.857	3.037	1.148	
women	7	15.357	3.66	1.383	
men	7	13.214	5.901	2.23	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	-2.5	6.236	0.575		
5 yr olds, men	-0.357	6.236	0.988		
women, men	2.143	6.236	0.664		

/p/ medians. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	225.595	112.798	0.347	0.712
Resid.	18	5855.357	325.298		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	7	50	26.3	9.94	
women	7	47.5	15.343	5.799	
men	7	42.143	6.986	2.641	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	2.5	25.705	0.967		
5 yr olds, men	7.857	25.705	0.722		
women, men	5.357	25.705	0.858		

Appendix D: ANOVA results

Median values: Results for all measures (see cover page)

/t/ medians. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	457.738	228.869	0.97	0.398
Resid.	18	4248.214	236.012		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	7	55.357	22.796	8.616	
women	7	60.714	8.256	3.12	
men	7	49.286	10.965	4.144	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	-5.357	21.895	0.81		
5 yr olds, men	6.071	21.895	0.764		
women, men	11.429	21.895	0.399		

Vdur1 medians. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	33209.269	16604.635	6.326	0.01
Resid.	15	39372.552	2624.837		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	4	209.314	100.368	50.184	
women	7	103.009	10.058	3.801	
men	7	109.436	37.737	14.263	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	106.305	87.145	0.016		
5 yr olds, men	99.878	87.145	0.024		
women, men	-6.427	74.318	0.973		

Vdur2 medians. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	5044.218	2522.109	0.894	0.428
Resid.	17	47983.698	2822.57		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	6	209.809	89.801	36.661	
women	7	176.143	20.342	7.689	
men	7	174.25	29.382	11.105	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	33.666	79.218	0.535		
5 yr olds, men	35.559	79.218	0.499		
women, men	1.893	76.11	0.998		

Appendix D: ANOVA results
Median values: Results for all measures (see cover page)

Pres. medians. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	0.896	0.448	0.139	0.872
Resid.	15	48.385	3.226		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	6	6.542	1.792	0.731	
women	6	6.333	1.966	0.803	
men	6	6	1.612	0.658	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	0.208	2.814	0.98		
5 yr olds, men	0.542	2.814	0.874		
women, men	0.333	2.814	0.95		

Pkflow medians. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	2235.714	1117.857	3.444	0.054
Resid.	18	5842.857	324.603		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	7	19.286	10.965	4.144	
women	7	35	27.538	10.408	
men	7	44.286	9.759	3.689	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	-15.714	25.677	0.289		
5 yr olds, men	-25	25.677	0.057		
women, men	-9.286	25.677	0.636		

VOTH medians. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	2750.595	1375.298	2.67	0.097
Resid.	18	9273.214	515.179		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	7	19.643	33.616	12.706	
women	7	27.143	20.383	7.704	
men	7	0	0	0	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	-7.5	32.348	0.828		
5 yr olds, men	19.643	32.348	0.294		
women, men	27.143	32.348	0.11		

Appendix D: ANOVA results

Mean values: Results for all measures except VOTH (see cover page)

/b/ means. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	24.327	12.164	0.429	0.658
Resid.	18	510.337	28.352		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	7	12.561	5.379	2.033	
women	7	12.49	6.423	2.428	
men	7	10.243	3.855	1.457	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	0.072	7.589	1		
5 yr olds, men	2.318	7.589	0.722		
women, men	2.247	7.589	0.736		

/d/ means. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	36.16	18.08	1.316	0.293
Resid.	18	247.244	13.736		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	7	11.955	3.904	1.475	
women	7	14.687	4.226	1.597	
men	7	11.855	2.847	1.076	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	-2.732	5.282	0.405		
5 yr olds, men	0.1	5.282	0.999		
women, men	2.832	5.282	0.38		

/p/ means. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	349.077	174.539	0.573	0.574
Resid.	18	5478.705	304.372		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	7	52.607	25.238	9.539	
women	7	48.056	14.764	5.58	
men	7	42.633	7.63	2.884	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	4.552	24.864	0.888		
5 yr olds, men	9.974	24.864	0.574		
women, men	5.423	24.864	0.846		

Appendix D: ANOVA results

Mean values: Results for all measures except VOTh (see cover page)

/t/ means. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	490.517	245.259	1.024	0.379
Resid.	18	4312.779	239.599		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	7	58.211	22.885	8.65	
women	7	61.26	8.322	3.145	
men	7	49.829	11.217	4.24	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	-3.05	22.061	0.935		
5 yr olds, men	8.382	22.061	0.607		
women, men	11.431	22.061	0.404		

Vdur1 means. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	34542.679	17271.34	7.067	0.007
Resid.	15	36658.596	2443.906		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	4	211.822	96.064	48.032	
women	7	103.176	9.074	3.43	
men	7	110.263	37.594	14.209	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	108.646	84.088	0.011		
5 yr olds, men	101.559	84.088	0.017		
women, men	-7.087	71.711	0.965		

Vdur2 means. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	7150.897	3575.448	1.278	0.304
Resid.	17	47565.937	2797.996		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	6	216.279	90.168	36.811	
women	7	176.553	19.174	7.247	
men	7	173.649	28.013	10.588	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	39.726	78.872	0.421		
5 yr olds, men	42.629	78.872	0.372		
women, men	2.904	75.778	0.995		

Appendix D: ANOVA results

Mean values: Results for all measures except VOTh (see cover page)

Pres. means. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	1.313	0.657	0.211	0.812
Resid.	15	46.709	3.114		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	6	6.709	1.773	0.724	
women	6	6.285	1.885	0.77	
men	6	6.058	1.627	0.664	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	0.424	2.765	0.918		
5 yr olds, men	0.652	2.765	0.817		
women, men	0.228	2.765	0.975		

Pkflow means. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	2313.821	1156.911	3.88	0.04
Resid.	18	5366.695	298.15		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	7	18.523	9.602	3.629	
women	7	34.498	26.025	9.837	
men	7	43.959	11.177	4.225	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	-15.975	24.609	0.25		
5 yr olds, men	-25.435	24.609	0.042		
women, men	-9.46	24.609	0.6		

VOTh means not computed given extreme non-normality of data.

Appendix D: ANOVA results

Standard Deviations: Results for all measures (see cover page)

/b/ SDs. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	12.985	6.493	1.35	0.284
Resid.	18	86.553	4.809		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	7	6.099	3.24	1.225	
women	7	4.744	1.497	0.566	
men	7	4.236	1.298	0.491	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	1.354	3.125	0.525		
5 yr olds, men	1.863	3.125	0.307		
women, men	0.509	3.125	0.911		

/d/ SDs. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	3.339	1.67	0.566	0.577
Resid.	18	53.071	2.948		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	7	5.864	1.128	0.426	
women	7	5.213	2.128	0.804	
men	7	6.169	1.745	0.659	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	0.65	2.447	0.781		
5 yr olds, men	-0.306	2.447	0.946		
women, men	-0.956	2.447	0.59		

/p/ SDs. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	425.674	212.837	10.349	0.001
Resid.	18	370.199	20.567		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	7	20.928	6.527	2.467	
women	7	11.953	2.119	0.801	
men	7	10.891	3.822	1.445	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	8.975	6.463	0.006		
5 yr olds, men	10.037	6.463	0.002		
women, men	1.062	6.463	0.909		

Appendix D: ANOVA results

Standard Deviations: Results for all measures (see cover page)

/t/ SDs. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	638.346	319.173	22.251	<.0001
Resid.	18	258.192	14.344		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	7	21.807	6.119	2.313	
women	7	10.365	2.103	0.795	
men	7	9.874	1.081	0.408	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	11.442	5.398	0		
5 yr olds, men	11.933	5.398	<.0001		
women, men	0.491	5.398	0.971		

Vdur1 SDs. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	2644.72	1322.36	15.734	0.0002
Resid.	15	1260.685	84.046		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	4	45.018	14.456	7.228	
women	7	14.182	4.589	1.734	
men	7	18.155	9.196	3.476	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	30.837	15.594	0.0003		
5 yr olds, men	26.864	15.594	0.0012		
women, men	-3.973	13.298	0.7249		

Vdur2 SDs. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	2976.889	1488.444	9.044	0.0021
Resid.	17	2797.702	164.571		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	6	41.853	22.421	9.153	
women	7	15.646	5.612	2.121	
men	7	14.834	3.984	1.506	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	26.207	19.128	0.007		
5 yr olds, men	27.019	19.128	0.0055		
women, men	0.812	18.378	0.993		

Appendix D: ANOVA results

Standard Deviations: Results for all measures (see cover page)

Pres. SDs. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	1.435	0.718	5.394	0.0172
Resid.	15	1.995	0.133		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	6	1.285	0.316	0.129	
women	6	0.641	0.243	0.099	
men	6	0.745	0.49	0.2	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	0.644	0.571	0.0264		
5 yr olds, men	0.54	0.571	0.0653		
women, men	-0.104	0.571	0.886		

Pkflow SDs. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	7.954	3.977	0.173	0.8429
Resid.	18	414.91	23.051		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	7	8.766	4.628	1.749	
women	7	7.698	5.814	2.198	
men	7	7.311	3.732	1.411	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	1.068	6.842	0.9174		
5 yr olds, men	1.455	6.842	0.8527		
women, men	0.387	6.842	0.9887		

VOTh SDs. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	1711.97	855.985	7.76	0.0037
Resid.	18	1985.567	110.309		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	7	30.307	11.127	4.206	
women	7	12.225	7.75	2.929	
men	7	10.237	12.126	4.583	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	18.082	14.969	0.0166		
5 yr olds, men	20.07	14.969	0.008		
women, men	1.987	14.969	0.9395		

Appendix D: ANOVA results

Coefficients of Variation: Results for selected measures (see cover page)

/p/ CoVs. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	0.152	0.076	9.728	0.0014
Resid.	18	0.141	0.008		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	7	0.434	0.134	0.051	
women	7	0.257	0.044	0.017	
men	7	0.25	0.06	0.023	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	0.177	0.126	0.0056		
5 yr olds, men	0.184	0.126	0.0041		
women, men	0.007	0.126	0.9904		

/t/ CoVs. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	0.195	0.097	18.081	<.0001
Resid.	18	0.097	0.005		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	7	0.393	0.11	0.042	
women	7	0.175	0.038	0.014	
men	7	0.206	0.051	0.019	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	0.218	0.105	0.0001		
5 yr olds, men	0.187	0.105	0.0007		
women, men	-0.031	0.105	0.7298		

Vdur1 CoVs. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	0.018	0.009	6.288	0.0104
Resid.	15	0.021	0.001		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	4	0.222	0.042	0.021	
women	7	0.139	0.036	0.014	
men	7	0.161	0.037	0.014	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	0.083	0.064	0.011		
5 yr olds, men	0.061	0.064	0.0625		
women, men	-0.022	0.055	0.5666		

Appendix D: ANOVA results

Coefficients of Variation: Results for selected measures (see cover page)

Vdur2 CoVs. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	0.041	0.021	13.009	0.0004
Resid.	17	0.027	0.002		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	6	0.188	0.057	0.023	
women	7	0.091	0.036	0.014	
men	7	0.087	0.023	0.009	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	0.097	0.059	0.0016		
5 yr olds, men	0.101	0.059	0.0011		
women, men	0.004	0.057	0.9825		

Pres. CoVs. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	0.034	0.017	4.299	0.0334
Resid.	15	0.06	0.004		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	6	0.204	0.081	0.033	
women	6	0.103	0.034	0.014	
men	6	0.124	0.065	0.027	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	0.101	0.099	0.0447		
5 yr olds, men	0.08	0.099	0.1213		
women, men	-0.021	0.099	0.8525		

Pkflow CoVs. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	0.464	0.232	4.656	0.0234
Resid.	18	0.898	0.05		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	7	0.525	0.253	0.096	
women	7	0.33	0.288	0.109	
men	7	0.161	0.051	0.019	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	0.195	0.318	0.2897		
5 yr olds, men	0.364	0.318	0.0236		
women, men	0.169	0.318	0.3849		

Appendix D: ANOVA results
Skew: Results for stop VOTs (see cover page)

/b/ skew. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	0.101	0.05	0.12	0.8872
Resid.	18	7.52	0.418		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	7	0.109	0.49	0.185	
women	7	0.154	0.711	0.269	
men	7	0.273	0.712	0.269	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	-0.046	0.921	0.9913		
5 yr olds, men	-0.164	0.921	0.8937		
women, men	-0.119	0.921	0.943		

/d/ skew. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	0.573	0.286	0.594	0.5625
Resid.	18	8.673	0.482		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	7	-0.093	0.341	0.129	
women	7	-0.461	0.876	0.331	
men	7	-0.421	0.749	0.283	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	0.369	0.989	0.6186		
5 yr olds, men	0.329	0.989	0.6813		
women, men	-0.04	0.989	0.9942		

/p/ skew. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	1.052	0.526	6.177	0.0091
Resid.	18	1.533	0.085		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	7	0.657	0.308	0.116	
women	7	0.219	0.3	0.113	
men	7	0.153	0.266	0.1	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	0.439	0.416	0.0378		
5 yr olds, men	0.504	0.416	0.0162		
women, men	0.066	0.416	0.9155		

Appendix D: ANOVA results
Skew: Results for stop VOTs (see cover page)

/t/ skew. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqr.	Mean Sqr.	F-Value	P-Value
Subj.group	2	0.373	0.186	0.891	0.4277
Resid.	18	3.765	0.209		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	7	0.369	0.417	0.158	
women	7	0.297	0.292	0.11	
men	7	0.057	0.607	0.23	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	0.071	0.652	0.9583		
5 yr olds, men	0.311	0.652	0.4598		
women, men	0.24	0.652	0.6253		

Skew/SE:

Results where ANOVA on skew was significant (see cover page)

/p/ skew/SE. Effect: Subj. group					
	DF	Sum of Sqr.	Mean Sqr.	F-Value	P-Value
Subj.group	2	3.362	1.681	2.83	0.0854
Resid.	18	10.695	0.594		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	7	1.433	0.639	0.241	
women	7	0.703	0.862	0.326	
men	7	0.502	0.795	0.3	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	0.73	1.099	0.2351		
5 yr olds, men	0.931	1.099	0.1055		
women, men	0.201	1.099	0.8885		

Appendix D: ANOVA results

Ranges of VOTH (all data and for VOTH>0); %VOTH=0 (see cover page)

VOTH ranges (all tokens). Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	20685.714	10342.857	9.203	0.0018
Resid.	18	20228.571	1123.81		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	7	107.143	34.983	13.222	
women	7	52.857	29.98	11.331	
men	7	32.857	35.338	13.357	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	54.286	47.777	0.0245		
5 yr olds, men	74.286	47.777	0.0024		
women, men	20	47.777	0.5476		
VOTH ranges (only for VOTH>0). Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	6512.518	3256.259	3.142	0.0746
Resid.	14	14511.012	1036.501		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	7	80.714	40.664	15.37	
women	6	54.167	21.311	8.7	
men	4	31.25	27.801	13.901	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	26.548	48.98	0.3605		
5 yr olds, men	49.464	55.181	0.0821		
women, men	22.917	56.828	0.5582		
%VOTH=0. Effect: Subj.group					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
Subj.group	2	9521.727	4760.863	5.263	0.0159
Resid.	18	16281.503	904.528		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
5 yr olds	7	55.857	24.712	9.34	
women	7	35.014	42.31	15.992	
men	7	86.843	17.684	6.684	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	20.843	42.863	0.4477		
5 yr olds, men	-30.986	42.863	0.1848		
women, men	-51.829	42.863	0.0165		

Appendix D: ANOVA results

Mean pressure values as a function of consonant (see cover page)

Pressure. Effects: Subj.group, C					
ANOVA Table	DF	Sum of Sqrs.	Mean Sqr.	F-Value	P-Value
C	2	40.909	20.455	5.998	0.0025
Subj.group	2	16.304	8.152	2.39	0.092
C * Subj.group	4	8.943	2.236	0.656	0.623
Resid.	1418	4835.727	3.41		
Means Table	Count	Mean	Std. Dev.	Std. Err.	
Effect: C * Subj.group					
b, Men	145	6.567	2.101	0.175	
b, Women	120	6.256	1.991	0.182	
b, 5 yr olds	55	6.597	1.97	0.266	
p, Men	257	5.982	1.745	0.109	
p, Women	196	5.93	1.654	0.118	
p, 5 yr olds	66	5.977	2.151	0.265	
h, Men	231	6.11	1.544	0.102	
h, Women	205	5.926	1.685	0.118	
h, 5 yr olds	152	6.433	2.269	0.184	
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
b, p	0.494	0.322	0.0009		
b, h	0.326	0.314	0.0397		
h, p	0.168	0.273	0.3201		
Scheffé test	Mean Diff.	Crit. Diff	P-Value		
5 yr olds, women	-0.352	0.338	0.0386		
5 yr olds, men	0.193	0.328	0.3516		
women, men	-0.159	0.268	0.3466		

Appendix E: Correlations among VOTH, size, f0, and aerodynamic measures

** p<.01 * .01<p<.05 ~.05≤p<.10

Correlation Matrix, all subjects except AF6-MP (N=20).

%VOTH=0	height	neck	min f0	midVf0	onset f0	Pkflow	ACflow	Pres
1.0								
height	1.0							
neck	.171	1.0						
min f0	.402~	.872**	1.0					
midV f0	-.280	-.802**	.910**	1.0				
onset f0	-.417~	-.843**	.908**	.984**	1.0			
Pkflow	-.440~	-.874**	.940**	.401~	-.461*	1.0		
ACflow	-.146	.551**	-.533**	-.292	-.344	.721**	1.0	
Pres (N=17)	.337	.357	-.374~	.102	.099	-.122	.135	1.0
Resis.	.079	-.216	.071	.306	.372	-.725**	-.557*	.310
	-.037	-.567*	.433~					

Correlation Matrix, Men only (N=7).

%VOTH=0	height	neck	min f0	midVf0	onset f0	Pkflow	ACflow	Pres
1.0								
height	1.0							
neck	.686	1.0						
min f0	.540	.265	1.0					
midV f0	-.513	-.054	.454	1.0				
onset f0	-.660	-.570	.659	.915	1.0			
Pkflow	-.725	-.533	-.287	.408	.490	1.0		
ACflow	-.751	-.284	-.019	.613	.611	.651	1.0	
Pres (N=6)	-.331	.077	.819	-.071	-.411	-.488	-.451	1.0
Resis (N=6)	.370	-.401	-.677	.151	-.300	-.764	-.358	.927
	.463	-.281	-.812					

Appendix E: Correlations among VOTh, size, f0, and aerodynamic measures

Correlation Matrix, Women only (N=6). Subject MP is not included (see text for discussion).

	%VOTh=0	height	neck	min f0	midVf0	onset f0	Pkflow	ACflow	Pres
%VOTh=0	1.0								
height	-.184	1.0							
neck	-.270	.757	1.0						
min f0	.280	.427	-.251	1.0					
midV f0	.287	-.379	-.454	.037	1.0				
onset f0	.007	-.268	-.705	.476	.727	1.0			
Pkflow	-.507	-.564	-.070	-.821	.217	-.044	1.0		
ACflow	-.349	-.604	-.224	-.643	.426	.139	.941	1.0	
Pres (N=5)	-.314	.626	.908	-.315	-.737	-.824	.123	.045	1.0
Resis (N=5)	.458	.632	.174	.782	-.647	-.124	-.993	-.962	-.001

Correlation Matrix, 5-year-olds only (N=7).

	%VOTh=0	height	neck	min f0	midVf0	onset f0	Pkflow	ACflow	Pres
%VOTh=0	1.0								
height	.021	1.0							
neck	-.267	.824	1.0						
min f0	.112	-.351	-.524	1.0					
midV f0	-.029	-.658	-.694	.829	1.0				
onset f0	-.049	-.785	-.811	.687	.962	1.0			
Pkflow	.087	-.107	-.068	.126	.353	.303	1.0		
ACflow	.831	-.207	-.461	.160	.272	.293	.543	1.0	
Pres (N=6)	.675	-.620	-.580	.065	.139	.226	-.058	.568	1.0
Resis (N=6)	.179	.047	-.004	-.250	-.546	-.446	-.863	-.336	.339

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**Appendix F: Correlation matrices for variables measured on /h/ within subjects,
for all tokens and where VOT_h>0 only**

In these tables, cases of significant or near-significant correlations are marked with asterisks or tildes (~) as follows:

- ** denotes $p < .01$
- * denotes $.01 \leq p \leq .05$
- ~ denotes $.05 < p \leq .10$

Shaded rows and columns indicate either 1) that no data were available (e.g., in cases where intraoral pressure recording was unsuccessful) or 2) that the analysis was inappropriate. For subjects who produced only fully voiced /h/, VOT_h values did not vary at all and thus could not be used for correlational analysis. Finally, since intraoral pressure was only collected for a portion of the recording session, the number of tokens available for correlation differed depending on whether pressure was included in the matrix or not. Therefore, correlations were performed twice for each speaker: Once without the pressure measures (thus, including all tokens), and once with the pressure measures (thus, including only tokens where a pressure signal was available). Correlations between pressure and the other variables are set off by a thin line to indicate that only a subset of the data are represented. The number of tokens included in the two analyses (i.e., without pressure/with pressure) are given after the speaker's identification code at the top left of each grid.

Appendix F: Correlation matrices for /h/ variables, all tokens: Men

RM: N=48/0	VOT _h	/h/ pk	AC flow	DC flow	Onset f ₀
VOT _h	1.0				
/h/ pk	.269 ~	1.0			
AC flow	.202	.288 *	1.0		
DC flow	-.742 **	.374 *	-.038	1.0	
Onset f ₀	.837 **	.081	.287 *	-.774 **	1.0
JG: N=28/28	VOT _h	/h/ pk	AC flow	DC flow	Onset f ₀
VOT _h	1.0				
/h/ pk		1.0			
AC flow		.478 **	1.0		
DC flow				1.0	
Onset f ₀		.221	.596 **		1.0
Pres		.288	.493 **		.212
DH: N=48/48	VOT _h	/h/ pk	AC flow	DC flow	Onset f ₀
VOT _h	1.0				
/h/ pk	.031	1.0			
AC flow	-.226	-.005	1.0		
DC flow	-.283 *	.939 **	.022	1.0	
Onset f ₀	.512 **	.024	-.384 *	-.074	1.0
Pres	.197	.268 ~	-.086	.206	.320 *
SL: N=30/30	VOT _h	/h/ pk	AC flow	DC flow	Onset f ₀
VOT _h	1.0				
/h/ pk	.430 *	1.0			
AC flow	-.492 *	-.693 **	1.0		
DC flow	-.147	.819 **	-.435 *	1.0	
Onset f ₀	.288	-.317 ~	.609 **	-.513 **	1.0
Pres	.167	.439 *	-.610 **	.376 *	-.375 *
LR: N=48/48	VOT _h	/h/ pk	AC flow	DC flow	Onset f ₀
VOT _h	1.0				
/h/ pk		1.0			
AC flow		-.465 **	1.0		
DC flow				1.0	
Onset f ₀		-.172	.543 **		1.0
Pres		.161	.322 *		.092
ED: N=40/40	VOT _h	/h/ pk	AC flow	DC flow	Onset f ₀
VOT _h	1.0				
/h/ pk	-.192	1.0			
AC flow	-.380 *	.253	1.0		
DC flow	-.749 **	.627 **	.264 ~	1.0	
Onset f ₀	.477 **	-.280 ~	-.070	-.553 **	1.0
Pres	-.194	.333 *	.178	.217	.052
BG: N=32/32	VOT _h	/h/ pk	AC flow	DC flow	Onset f ₀
VOT _h	1.0				
/h/ pk		1.0			
AC flow		-.328 ~	1.0		
DC flow				1.0	
Onset f ₀		.215	.601 **		1.0
Pres		-.139	.222		.221

Appendix F: Correlation matrices for /h/ variables, all tokens: Women

DR: N=36/24	VOT _h	/h/ pk	AC flow	DC flow	Onset f ₀
VOT _h	1.0				
/h/ pk	.273	1.0			
AC flow	.200	.813 **	1.0		
DC flow	-.030	.438 *	-.018	1.0	
Onset f ₀	.200	.515 **	.627 **	-.353 *	1.0
Pres	.059	-.431 *	-.518 *	.636 **	-.753 **
MS: N=23/23	VOT _h	/h/ pk	AC flow	DC flow	Onset f ₀
VOT _h	1.0				
/h/ pk	-.149 ~	1.0			
AC flow	.163	-.381	1.0		
DC flow	-.346 **	.844 **	-.666 **	1.0	
Onset f ₀	.025	-.164	.680 **	-.482 *	1.0
Pres	-.385 ~	.022	.073	.036	.155
PC: N=44/44	VOT _h	/h/ pk	AC flow	DC flow	Onset f ₀
VOT _h	1.0				
/h/ pk	.242	1.0			
AC flow	-.178	-.276 ~	1.0		
DC flow	-.182	.873 **	-.204	1.0	
Onset f ₀	.071	-.139	-.207	-.280 ~	1.0
presamp	-.060	-.277 ~	-.072	-.367 *	.371 *
DB: N=48/48	VOT _h	/h/ pk	AC flow	DC flow	Onset f ₀
VOT _h	1.0				
/h/ pk	.056	1.0			
AC flow	.245 ~	-.047	1.0		
DC flow	-.736 **	.531 **	-.346 *	1.0	
Onset f ₀	.496 **	.033	-.033	-.305 *	1.0
Pres	-.185	.319 *	-.212	.335 *	-.147
MD: N=40/20	VOT _h	/h/ pk	AC flow	DC flow	Onset f ₀
VOT _h	1.0				
/h/ pk	.431 *	1.0			
AC flow	.380 *	.296 ~	1.0		
DC flow	-.267 ~	.601 **	-.244	1.0	
Onset f ₀	.576 **	.297 ~	.027	-.209	1.0
Pres	.142	.778 **	.498 *	.676 **	.125
MP: N=45/45	VOT _h	/h/ pk	AC flow	DC flow	Onset f ₀
VOT _h	1.0				
/h/ pk		1.0			
AC flow		.423 **	1.0		
DC flow				1.0	
Onset f ₀		.128	-.167		1.0
Pres		.319 *	.350 *		.202
LK: N=53/0	VOT _h	/h/ pk	AC flow	DC flow	Onset f ₀
VOT _h	1.0				
/h/ pk	.331 *	1.0			
AC flow	.242 ~	.299 *	1.0		
DC flow	-.578 **	.014	-.508 **	1.0	
Onset f ₀	.365 **	.181	.147	-.345 *	1.0
Pres					

Appendix F: Correlation matrices for /h/ variables, all tokens: 5-year-olds

DJ: N=38/35	VOTH	/h/ pk	AC flow	DC flow	Onset f0
VOTH	1.0				
/h/ pk	.610 **	1.0			
AC flow	-.674 **	-.448 **	1.0		
DC flow	-.833 **	-.250	.665 **	1.0	
Onset f0	.777 **	.474 **	-.603 **	-.808 **	1.0
Pres	.263	.422 *	-.234	-.099	.146
SS: N=22/21	VOTH	/h/ pk	AC flow	DC flow	Onset f0
VOTH	1.0				
/h/ pk	.397 ~	1.0			
AC flow	-.638 **	-.021	1.0		
DC flow	-.331	.601 **	.384 ~	1.0	
Onset f0	.491 *	.193	-.027	-.371 ~	1.0
Pres	.037	.208	.151	.090	.062
HJ: N=30/30	VOTH	/h/ pk	AC flow	DC flow	Onset f0
VOTH	1.0				
/h/ pk	.364 *	1.0			
AC flow	-.240	.038	1.0		
DC flow	-.024	.838 **	-.071	1.0	
Onset f0	-.001	.145	-.456 *	.345 ~	1.0
Pres	.058	.095	.332 ~	.054	-.123
EC: N=12/12	VOTH	/h/ pk	AC flow	DC flow	Onset f0
VOTH	1.0				
/h/ pk	-.102	1.0			
AC flow	-.501 ~	.399	1.0		
DC flow	-.616 *	.838 **	.601 *	1.0	
Onset f0	-.123	-.689 *	-.376	-.493	1.0
Pres	-.683 *	.330	.757 **	.642 *	-.116
HH: N=38/20	VOTH	/h/ pk	AC flow	DC flow	Onset f0
VOTH	1.0				
/h/ pk	.379 *	1.0			
AC flow	-.406 *	-.019	1.0		
DC flow	-.363 *	.506 **	.214	1.0	
Onset f0	.357 *	.448 **	.040	-.050	1.0
Pres	-.332	-.221	.201	.051	-.022
LEZ: N=22/0	VOTH	/h/ pk	AC flow	DC flow	Onset f0
VOTH	1.0				
/h/ pk	-.075	1.0			
AC flow	-.435 *	.117	1.0		
DC flow	-.477 *	.901 **	.277	1.0	
Onset f0	-.057	.033	.518 *	.064	1.0
MM: N=41/30	VOTH	/h/ pk	AC flow	DC flow	Onset f0
VOTH	1.0				
/h/ pk	.124	1.0			
AC flow	-.375 *	-.073	1.0		
DC flow	-.228	.918 **	.071	1.0	
Onset f0	-.160	.136	.731 **	.199	1.0
Pres	-.135	.152	.453 *	.229	.719 **

Appendix F: Correlation matrices for /h/ variables, VOTH>0: Men

RM: N=19/0	VOTH	Pkflow	AC flow	DC flow	Onset f0
VOTH	1.0				
Pkflow	.482 *	1.0			
AC flow	.201	.474 *	1.0		
DC flow	-.206	.464 *	.215	1.0	
Onset f0	.030	.298	.440 ~	.321	1.0
ED: N=15/7	VOTH	Pkflow	AC flow	DC flow	Onset f0
VOTH	1.0				
Pkflow	-.397	1.0			
AC flow	-.002	.603 *	1.0		
DC flow	-.816 **	.541 *	-.054	1.0	
Onset f0	.461 ~	-.322	-.125	-.550 *	1.0
Pres	-.136	.557	.408	.211	.140

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Appendix F: Correlation matrices for /h/ variables, VOT_h>0: Women

DR: N=27/18	VOT _h	Pkflow	AC flow	DC flow	Onset f0
VOT _h	1.0				
Pkflow	.624 **	1.0			
AC flow	.627 *	.803 **	1.0		
DC flow	.052	.560 **	.100	1.0	
Onset f0	.462 **	.488 **	.585 **	-.225	1.0
Pres	-.256	-.374	-.342	.579 *	-.751 **
†MS: N=23/23	VOT _h	Pkflow	AC flow	DC flow	Onset f0
VOT _h	1.0				
Pkflow	-.149 ~	1.0			
AC flow	.163	-.381	1.0		
DC flow	-.346 **	.844 **	-.666 **	1.0	
Onset f0	.025	-.164	.680 **	-.482 *	1.0
Pres	-.385 ~	.022	.073	.036	.155
DB: N=40/40	VOT _h	Pkflow	AC flow	DC flow	Onset f0
VOT _h	1.0				
Pkflow	-.019	1.0			
AC flow	.051	.001	1.0		
DC flow	-.541 **	.688 **	-.210	1.0	
Onset f0	.138	.069	-.227	.165	1.0
Pres	.231	.339 *	-.210	.036	.019
MD: N=35/16	VOT _h	Pkflow	AC flow	DC flow	Onset f0
VOT _h	1.0				
Pkflow	.162	1.0			
AC flow	.447 **	.346 *	1.0		
DC flow	-.471 **	.627 **	-.217	1.0	
Onset f0	.417 *	.091	.013	-.307 ~	1.0
Pres	-.195	.829 **	.568 *	.667 **	.059
†LK: N=53/0	VOT _h	Pkflow	AC flow	DC flow	Onset f0
VOT _h	1.0				
Pkflow	.331 *	1.0			
AC flow	.242 ~	.299 *	1.0		
DC flow	-.578 **	.014	-.508 **	1.0	
Onset f0	»-.365 **	.181	.147	»-.345 *	1.0

† These subjects had no tokens of VOT_h=0, so the matrices shown here are identical to those given above in this appendix. The dataset for AF7/LK includes 1 token with very short VOT_h (about a pulse-long voicing break). Removing this token generally yielded lower r-values and reduced significance levels. Cases where significance levels dropped markedly are indicated here with (»).

Appendix F: Correlation matrices for /h/ variables, VOTH>0: 5-year-olds

DJ: N=25/25	VOTH	Pkflow	AC flow	DC flow	Onset f0
VOTH	1.0				
Pkflow	.474 *	1.0			
AC flow	.061	-.319	1.0		
DC flow	-.089	.322	-.058	1.0	
Onset f0	.130	.141	-.293	-.593 **	1.0
Pres	.206	.435 *	-.247	.248	-.032
SS: N=10/9	VOTH	Pkflow	AC flow	DC flow	Onset f0
VOTH	1.0				
Pkflow	.237	1.0			
AC flow	-.631 *	.282	1.0		
DC flow	-.341	.479	.295	1.0	
Onset f0	.394	.240	.008	-.399	1.0
Pres	.436	.450	-.313	-.021	.162
HJ: N=13/13	VOTH	Pkflow	AC flow	DC flow	Onset f0
VOTH	1.0				
Pkflow	-.035	1.0			
AC flow	.124	.592 *	1.0		--
DC flow	-.329	.872 **	.236	1.0	
Onset f0	-.528 ~	-.199	-.709 **	.129	1.0
Pres	-.140	.136	.192	.107	-.023
HH: N=30/17	VOTH	Pkflow	AC flow	DC flow	Onset f0
VOTH	1.0				
Pkflow	.317 ~	1.0			
AC flow	-.306 ~	-.005	1.0		
DC flow	.082	.770 **	-.137	1.0	
Onset f0	.027	.325 ~	.211	.114	1.0
Pres	-.333	-.290	.164	-.343	.048

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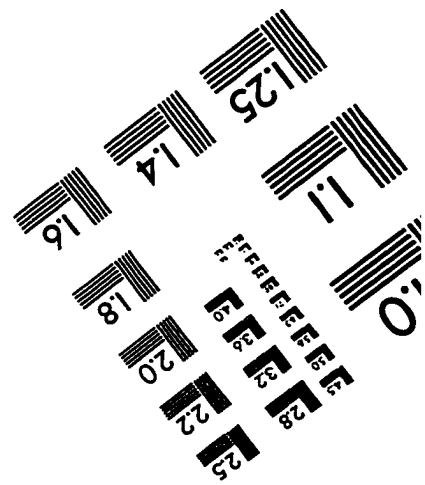
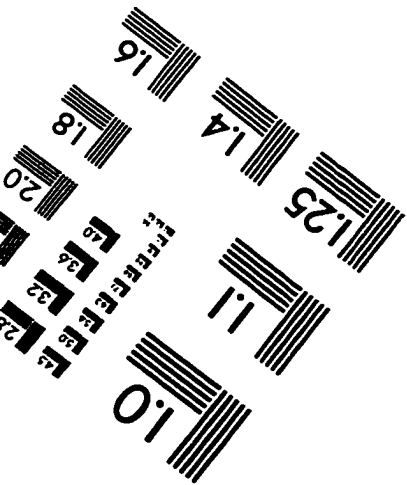
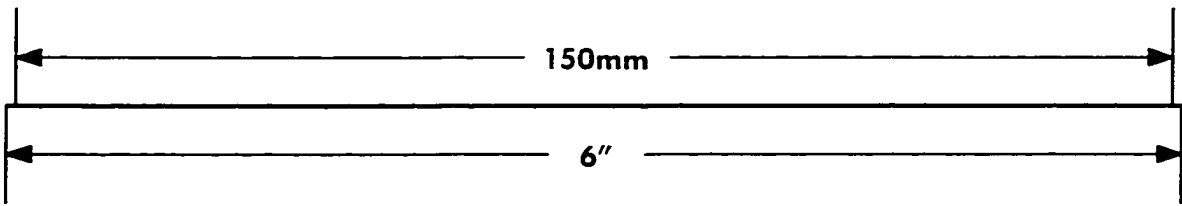
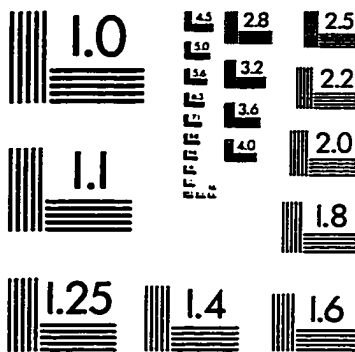
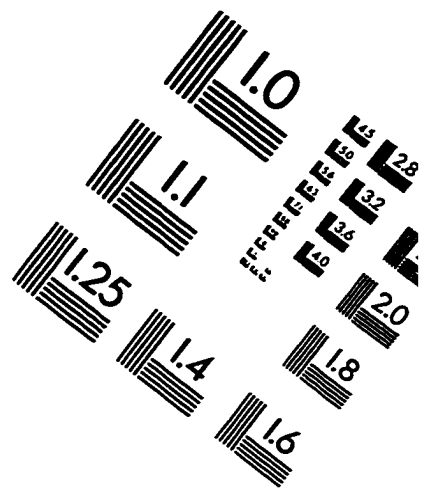
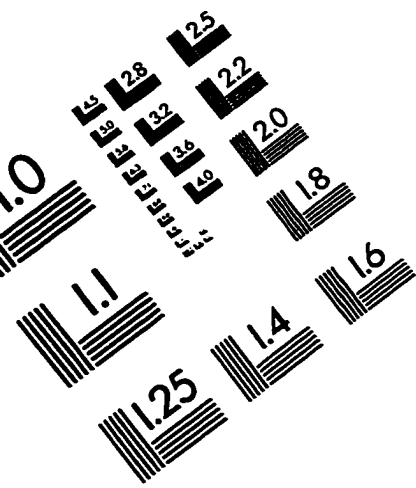
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IMAGE EVALUATION TEST TARGET (QA-3)



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