VOICE ONSET TIME (VOT) OF VOICED AND VOICELESS INITIAL STOPS AND INITIAL /S/+STOP CONSONANT CLUSTERS IN MONOLINGUAL ENGLISH-SPEAKING ADULTS AND 4-YEAR-OLD CHILDREN

by

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THESIS APPROVAL

The abstract and thesis of Jennifer Weber for the Master of Science in Speech and Hearing Sciences were presented June 7, 2007, and accepted by the thesis committee and the department.

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ABSTRACT

An abstract of the thesis of Jennifer Weber for the Master of Science in Speech and Hearing Sciences presented June 7, 2007.

Title: Voice Onset Time (VOT) Of Voiced and Voiceless Initial Stops and Initial /s/+Stop Consonant Clusters in Monolingual English-speaking Adults and 4-year-old Children.

Voice onset time (VOT) of initial voiced stops, /s/+stop clusters, and voiceless stops were compared in the speech of 30 monolingual English-speaking adults and 37 monolingual English-speaking 4-year-old children. Acoustic duration measurements were used to understand if phonemic and allophonic VOT distinctions are significant in adults and whether 4-year-olds show the same patterns. Results suggest that children and adults produce the three types of stops with significantly different VOT means, and distinct ranges and distributions. The results also indicate that 4-year-old English-speaking children are still in the process of developing adult-like VOT values for voiced stops. The continued development of VOT values for voiced stops appears to result from an increasing percentage of voiced stops produced with lead VOT values. The results also suggest that children may produce a stop for reduced /s/+stop clusters with VOT values unique from their voiced or voiceless stops.

DEDICATION

To my family and friends.

Thank you for your support.

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I am very appreciative for all of the support I received while completing my thesis.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Introduction

An understanding of speech development is important within the field of speech-language pathology for valid assessment and treatment of children with speech sound delays and disorders. This study will provide information about the acquisition of a specific speech parameter, voice onset time (VOT), by comparing VOT values in the speech of 4-year-old children and adults. It will also provide normative VOT values to use in future investigations of bilingual speech development and disordered speech.

VOT is an empirical acoustic measure that differentiates voicing in initial stops. Voicing contrasts allow listeners to distinguish certain sounds within a language that are otherwise produced identically. For example, two English stops that differ only in voicing are “p” and “b.” VOT has also been used to characterize the stop in /s/+stop consonant clusters such as “sp.”

In order for children to produce these stop consonant contrasts, they must acquire the voicing distinction that is characteristic of English. Different theories of speech development influence the expectations for how children acquire sounds and sound distinctions. Based on previous research on the development of VOT, this study has adopted a theory of speech development based primarily on general physiological development. Theories of this nature focus on perceptual, motor, and cognitive functions that have evolved to support speech development. Development is explained through changes in the physiological capabilities and limitations of the speech system.

Given this perspective, gradual changes in VOT values would be expected as the children's systems develop and the voicing distinction is acquired.

Literature Review

Adult Speech

VOT of initial stops. VOT, as described in Lisker and Abramson's seminal 1964 study, is the primary acoustic feature that distinguishes voicing for homorganic stops. VOT is defined as the time difference between the release of closure for a stop consonant and the onset of vocal fold vibration. Based on their analysis of VOT in 11 languages, Lisker and Abramson (1964) concluded that there are three major categories of VOT across languages: lead voicing, short-lag VOT, and long-lag VOT. Lead voicing occurs when vocal fold vibration begins before release of closure for the stop. Short-lag VOT occurs when vocal fold vibration begins almost instantaneously after release of closure, and long-lag voicing occurs when vocal fold vibration begins well after release of the closure (Ladefoged, 2001)

English utilizes three places of articulation for the production of oral stops, bilabial, alveolar, and velar. At each place of articulation English speakers produce two stops, one described as "voiced" and the other described as "voiceless." The voicing difference allows listeners to differentiate the following stops: b/p (bilabial), d/t (alveolar), and g/k (velar) [For example, the voicing contrast in these initial stops allows listeners to perceive the difference between "pie" and "bye," "tie" and "dye," and "gap" and "cap"]. The voiced/voiceless distinction in English is generally described as a short-lag/long-lag VOT distinction. Lead voicing is allophonic in English, which means that producing voiced stops with lead voicing does not change meaning. In other words, in English, a “b” will be perceived as a “b” regardless of whether it is produced with lead voicing or short-lag voicing.

Several studies have reported VOT values of English-speaking adults. Many of these studies have only included stops produced in the short-lag and long-lag categories, excluding or separating productions with lead voicing. Other studies have revealed that English speakers use lead voicing frequently in the production of voiced stops. Zlatin (1974) found that 18 out of 20 subjects used lead voicing when reading single words for at least one place of articulation, and 9 used it at all places of articulation. Furthermore, she found that if adults used lead voicing they used it for approximately 33% of their voiced stops. Flege (1982) reported that as many as half of voiced stops were produced with lead voicing in the studies he reviewed.

The inclusion of lead voicing has a large impact on VOT means. Table 1 provides VOT values from studies that did and did not include lead voicing (negative VOT). Lisker and Abramson (1964) chose to report separate means for voiced stops produced with lead voicing because only one of their 4 English-speaking subjects used lead voicing consistently. Both means reported by Lisker and Abramson (1964) are presented. As can be seen in Table 1, studies that are inclusive of lead voicing generally have negative VOT values for voiced stops. Another aspect of VOT illustrated in Table 1 is the effect of place of articulation on VOT. VOT values typically increase as the point of closure moves back in the oral cavity (Lisker & Abramson, 1964; Cho & Ladefoged, 1999).

Table 1

Adult Norms for VOT (msec) in Studies Inclusive and Not Inclusive of Lead Voicing

Research studies that did not include lead voicing	Bilabial		Alveolar		Velar	
	B	**p**	**d**	**t**	**g**	**K**
Klatt, 1975 n = 3 Stimuli - "say ________ instead"	11	47	17	65	27	70
Smit & Bernthal, 1983 n=11 Stimuli – "the _______ away"	12.7	49.7	24.4	86.6	35.1	95.5
Lisker & Abramson, 1964 n = 3 Stimuli – single words	1	58	5	70	21	80
Byrd, 1993 n=630 Stimuli – TIMIT database of read English	18	44	24	49	27	52
Research studies that included lead voicing	**Bilabial**		**Alveolar**		**Velar**	
	b	**p**	**d**	**t**	**g**	**K**
Lisker & Abramson, 1964 n = 1 Stimuli – single words	-101	-	-102	-	-88	-
Zlatin, 1974 n=20 Stimuli – single words	-23.17	78.99	-5.20	87.12	-0.08	90.73
Ryalls & Zipprer, 1997 n=10 (male) Stimuli – single words	-14	67	-43	82	-31	87
Ryalls & Zipprer, 1997 n=10 (female) Stimuli – single words	-7	77	-10	95	12	87

VOT of /s/ + stop clusters. Less is known about VOT of stops in the /s/+stop consonant clusters, /sp/, /st/, and /sk/. Studies by Klatt (1975), and Smit and Bernthal (1983) investigated VOT in /s/+stop clusters. Their mean VOT values are presented in Table 2. Both studies found that the stops in /s/+stop clusters were produced with short-lag voicing. They concluded that the stop in /s/+stop clusters resembled voiced stops, which also had short-lag VOT values. However, neither study included instances of voiced stops produced with lead voicing in their analysis. Klatt (1975) did not include instances of lead voicing because, “The presence or absence of prevoicing is not phonemic in English and is frequently difficult to establish spectrographically because of the limited dynamic range of the spectrogram paper” (p. 688). The VOT values of /s/+stop clusters in these studies may have appeared more similar to voiced stops than if lead voicing had been included. Therefore, these figures may provide incomplete adult norms with which to compare developing speech.

Table 2

Mean VOT Values (msec) for Initial Stops and /s/+stop Clusters

Research Study	b	Sp	p	d	St	t	g	Sk	k
Klatt, 1975 n = 3 Stimuli: “say ________ instead"	11	12	47	17	23	65	27	30	70
Smit & Bernthal, 1983 n=11 Stimuli: “the _______ away”	12.7	13.8	49.7	24.4	34.5	86.6	35.1	34.2	95.5

Developing Speech

Accurate information about adult speech is important when investigating developing speech in that adult speech represents a fully developed speech system and provides end points with which to compare children’s speech.

The field of speech and language pathology uses a developmental approach to the assessment and treatment of speech disorders. During assessment of children’s speech, their productions are compared to what is considered normal for their age range and to what is considered normal for adults. When a disorder is identified, different perspectives on how speech develops dictate different treatment approaches.

Theories of speech development. The field of speech and language pathology has historically approached speech development from two theoretical perspectives. One approach focuses on the phonological representation of sounds. This approach generally assumes that children are born with an innate representation that is modified during development to form an adult system. This process is thought to involve the activation and modification of features and rules that govern the phonological representation (Grunwell, 1997; Hodson & Paden, 1983; Ingram, 1997).

In contrast, speech development can also be viewed as a constructivist process primarily based on physiological information. From this perspective speech develops in conjunction with and dependent on perceptual, motor and cognitive development. Perceptual developments enable children to attend to the speech streams they hear and parse out the words, syllables and phonemes that are meaningful in their native language (Jusczyk, 1999; Werker & Tees, 1999). In addition, increasing cognitive abilities enable children to process acoustic information, connect the acoustic information to language, formulate expressive language, and plan the motor movements required to produce the sounds (Lalande & Werker, 1995; Locke & Pearson, 1992; Werker & Tees, 1999). Finally, this perspective requires that children develop the motor capabilities to produce speech with appropriate coordination, control and timing (Kent, 1997; Thelen, 1991).

These perspectives are not mutually exclusive and may be combined to form a single view of speech development. Within the field of speech and language pathology, theoretical perspectives have implications for identification and treatment of speech sound disorders. Previous research on the development of the voicing contrast has indicated that it is more of a physiologically based process, as characterized below. This perspective has been adopted in this investigation.

VOT of initial stops in developing speech. Several studies have investigated speech development of voiced and voiceless stops by measuring VOT. The general pattern described is a progression from (a) a broad range of VOT values with no apparent voicing distinctions being made, (b) short-lag productions dominant with no voicing distinctions being made, (c) voicing distinctions made within the short-lag and long-lag categories, though long-lag productions are not adult-like, and (d) long-lag productions become more adult-like and voicing lead begins to appear. This progression is based on a number of studies looking at different languages, including:

1) English monolingual children (Eilers, Oller & Benito-Garcia, 1984; Gilbert, 1977; Kewley-Port & Preston, 1974; Macken & Barton, 1980).

2) Spanish monolingual children (Eilers, Oller & Benito-Garcia, 1984; Macken & Barton, 1979).

3) Spanish and English bilingual children (Deuchar & Clark, 1996; Konefal & Fokes, 1981).

4) Thai monolingual children (Gandour, Holasuit Petty, Dardarananda, Dechongkit & Mukngoen, 1986).

5) English and Japanese bilingual children (Johnson, & Wilson 2002).

Studies that investigated VOT development in English-speaking children are outlined in Table 3.

Table 3

Summary of Results from Studies Investigating VOT in English-Speaking Children

Study	Stimuli	Summary of Findings
Kewley-Port & Preston (1974)	/d/ and /t/ in spontaneous speech Participants repeated utterances of one of the 2-year old children.	**One 7-month old:** Broad distribution of VOT values with no mode **Three children 1 to 2 years of age:** VOT values distributed around a single mean in the short-lag category. **One child 3;6, three children 4;6 and three adults:** Adult-like productions of /d/ were established in the speech of both groups of children. Both groups had a wider range of VOT values than the adults, with no mode.
Eilers, Oller, & Benito-Garcia (1984)	Canonical utterances Imitated syllables	**Seven children 8-months to 1;2**: Voiced and voiceless Undifferentiated stops produced in the short-lag category. **Re-examined children speech at 2 years:** Significantly different voiced and voiceless stops, but predominately produced with short-lag.
Macken & Barton (1979)	Spontaneous speech	**Four children 1;6 to 2;2, longitudinal:** Significant differences between means for voiced and voiceless pairs. The children produced stops within increasingly discrete VOT ranges as they developed.
Gilbert (1977)	/d/ and /t/ Spontaneous speech	**Six children 2;7 to 3;3:** /d/ produced with short-lag voicing with adult-like means and distributions. Majority of /t/ sounds were produced with long-lag voicing, but with a broader distribution than adult values. Adult comparisons were based on Lisker and Abramson's VOT categories of adult speech (1964).

Physiological framework of VOT development. Studies of VOT in development have evidenced gradual changes during the acquisition of the voicing contrast. Kewley-Port and Preston (1974) provided an articulatory explanation for the pattern of VOT development described in the preceding section. Their explanation is rooted in the idea that each voicing category requires different timing between glottal closure and stop closure and release. They described how producing stops with differentiated VOT values requires children to plan, coordinate, and execute complex motor acts with specific timing and phasing. The following is their outline of the articulatory mechanisms involved for each VOT category:

Short-lag

1. Close glottis to begin voicing at any time during stop closure.
2. Release stop closure and begin voicing.
3. Transglottal pressure difference for vocal fold vibration is easily maintained.

Long-lag

1. Keep glottis open during stop closure.
2. Release stop closure.
3. Close glottis to begin voicing.

Lead voicing

1. Close glottis to begin voicing during stop closure.
2. Start voicing during stop closure keeping transglottal pressure difference by some other articulatory mechanism.
3. Release stop.

Based on the motor acts involved for each category, Kewley-Port and Preston (1974) felt that short-lag stops are the easiest to produce. They explained that lead stops and long-lag stops may require additional articulatory control. For lead stops control is necessary to allow air to pass through the glottis for voicing, while continuing to block air from leaving through the mouth to maintain the stop closure. Long-lag stops were described as harder to produce because of the need to control timing between glottal and supraglottal articulators such that there is a sufficient time delay between release of the stop and the onset of voicing.

Zlatin and Koenigsknecht (1976) discussed seven changes related to VOT during speech development in English. The changes they described are (a) changes in phoneme boundary width, (b) changes in mean VOT values, (c) increase in mean lead time, (d) increase in the percentage of lead for voiced stops, (e) changes to the range of productions for each category, (f) increased discreteness of voicing categories, and (g) increased correlation between perception and production. These changes support the idea that acquisition of voicing distinctions results from maturation of the systems involved in both the perception and production of speech. Two of the changes Zlatin and Koenigsknecht describe involve the use of lead voicing. Therefore it is important to consider the role of lead voicing in development.

Lead VOT in developing speech. Studies examining the development of the voicing contrast in monolingual English-speaking children have generally ignored lead voicing. Several studies report instances of lead voicing but do not include lead voicing in their discussions (Bond & Wilson, 1980; Catts & Kamhi, 1984; Eilers, Oller, & Benito-Garcia, 1984; Macken & Barton, 1979). Other studies have reported that no instances of lead voicing were recorded (Gilbert, 1977; Kewley-Port & Preston, 1974) or did not include lead voicing in their investigation (Smit & Bernthal, 1983).

Development of lead voicing has been studied in other languages that have a phonemic contrast between lead voicing and short-lag voicing. These studies have found that lead voicing is acquired later than short-lag or long-lag voicing. Macken and Barton (1980) looked at VOT development in Spanish, a language that uses lead VOT for voiced stops and short-lag VOT for voiceless stops. They found that the Spanish-speaking children were not yet using lead voicing consistently by age 4. This was in contrast to the English-speaking children in their 1979 study who were producing both short-lag and long-lag stops by age 2;6. Similarly, Allen (1985) stated that children acquiring French, a language that uses a voicing contrast similar to Spanish, also acquire lead voicing later in development than English-speaking children.

Lead voicing has also been investigated in the speech of children learning languages that have a phonemic distinction between all three categories of voicing. Gandour, Holasuit Petty, Dardarananda, Dechongkit, and Mukngoen (1986) examined VOT in Thai, a language that uses lead, short-lag, and long-lag voicing to differentiate three stops at the bilabial and alveolar places of articulation. Their subjects included seven 3-year-olds, seven 5-year-olds, seven 7-year-olds, and seven adults. Every age group produced short-lag and long-lag stops with VOT values similar to adult productions, but the use of lead voicing increased with age. In another study, Deuchar and Clark (1996) examined the productions of a bilingual child who spoke English (short-lag and long-lag voicing) and Spanish (lead voicing and short-lag voicing). At age 2;3, the child had acquired the short-lag/long-lag contrast of English, but was not yet using lead voicing in his Spanish productions. These studies support the idea that lead voicing is inherently more difficult to produce then short-lag or long-lag voicing.

Development of /s/+stop clusters. One way that English builds its lexicon is through increasing phonetic complexity. This is achieved in many ways, including within-syllable sequences of consonants, or consonant clusters. For example, when /s/ is added in front of the word "pie" a new word, "spy," is created.

An understanding of cluster development in children's speech is important to speech-language pathologists. Clusters are prevalent in English and cluster errors contribute to overall unintelligibility of children (McLeod, Van Doorn, & Reed, 2001; Hodson & Paden, 1983). In general, clusters begin emerging at age 2 and typically follow the acquisition pattern described below (McLeod, Van Doorn, & Reed, 2001; Smit, 1993):

1. One-element realization – The cluster is reduced to a single sound.
2. Two-element realization – The cluster comprises two sounds, but the sounds may be substitutions for the accurate sounds.
3. Correct realization.

In English, /s/+stop clusters follow this general developmental pattern. Table 4 presents figures for the typical age at which /s/+stop clusters are produced correctly by 75% of children (McLeod, Van Doorn, & Reed, 2001).

Table 4

Age of Acquisition (75% criterion) for /sp,st,sk/

Smit et al. (1990): Females	4;6 years
Smit et al. (1990): Males	5;0-6;0 years
Templin (1957)	4;0 years
Higgs (1968)	4;6 years

Reduced /s/+stop clusters. Before children accurately produce /s/+ stop clusters, they typically produce them as single stops (Bond & Wilson, 1980; Catts & Kamhi, 1984). Within the field of speech and language pathology this error is generally described as the process of cluster reduction. The nature of the resulting stop remains unclear. From a physiological perspective the nature of the stop produced would depend on how children perceive the stop and what they were capable of producing.

There are two factors that would lead to reduced /s/+stop clusters being realized as voiced stops. First, in Klatt's (1975) data of VOT for /s/ + stop clusters, adults produced the clusters in the short-lag category. Therefore, if the /s/ portion of the production were removed these stops may be perceived as voiced. This was supported by the work of Pegg and Werker (1997) who found that infants did not perceptually discriminate between /d/ and /st/ when the /s/ was removed. Adults were able to detect the difference between sounds, but performed at a level below what would be expected if the difference was phonemic. Secondly, according to Kewley-Port and Preston (1974), stops in the short-lag region are easier to produce than long-lag stops. Therefore, voiced stops may be a preferred substitution based on ease of articulation.

The reduced /s/ + stop clusters may also be produced as voiceless stops. Even without including lead voicing, Both Klatt (1975) and Smit and Bernthal (1983) found that the VOT values for /s/ + stop clusters in adult productions are slightly larger then in voiced stops. When lead voicing is considered, VOT values of /s/+stops may be significantly larger than voiced stops. Children may perceive the larger VOT values of /s/+stop clusters and reduce them to the voiceless stop.

Studies of VOT in reduced clusters have found individual variation in children's productions of these stops. Studies of 2-year-old children and 4 to 6-year old children with speech sound disorders found that children produced the majority of their reduced /s/+stop clusters as voiced stops (Catts & Kamhi, 1984; Scobbie, Hardcastle, Fletcher, & Gibbon, 1995). However, Bond and Wilson (1980) found that half of their participants between 1;0 and 3;6 years of age produced the majority of reduced clusters in the long-lag range.

Smit and Bernthal (1983) performed a more in-depth analysis of VOT in /s/+stop productions of older children aged 4;6 to 5;5. Children who reduced the clusters were inconsistent in their realizations. Some produced singletons equivalent to their voiced stops and some produced singletons equivalent to their voiceless stops. While more comprehensive, this study did not include instances of lead voicing. As with other studies that did not include lead voicing of voiced stops, the similarity between VOT for the reduced clusters and voiced stops may have been exaggerated.

Purpose of the Study

This study compared VOT of stops in /s/+stop clusters to voiced stops and voiceless stops in monolingual English-speaking adults and 4-year-old children. The key factor in this analysis was the inclusion of lead voicing in the VOT calculations. Previous comparisons of /s/+stop clusters and initial stops chose not to include lead voicing in their analysis. Those studies found that voiced stops and /s/+stop clusters were produced with very similar VOT values. Studies have also shown that by 4 years of age, English-speaking children have acquired the voicing distinction between voiced and voiceless stops. However, because lead voicing has not been included, the maturity of this distinction remains unknown. The primary aim of this experiment was to see how these three categories compare when lead voicing is included.

Previous research on VOT in developing speech has been performed on small samples of children with limited comparisons to adult norms. The adult VOT values generated in this study provided study-specific normative data on a large sample of adults to compare with children's developing speech. By creating study-specific norms, more valid comparisons were made between the adult speakers and child speakers. In order to strengthen the comparisons, the adults' data was gathered from the same geographic region using similar stimuli, similar equipment, and similar techniques as the children's data.

Children between 4;0 and 5;0 years of age were expected to produce fully realized /s/+stop clusters. However, some productions of reduced clusters were anticipated. These instances of reduced clusters were examined separately and the nature of the resulting stop examined in terms of VOT.

Hypotheses

The three hypotheses examined in this study were:

1) Adults will produce voiced stops, /s/+stop clusters, and voiceless stops with significantly different VOT values. These should be produced with lead voicing, short-lag voicing, and long-lag voicing respectively.

2) 4-year-old children will produce voiced stops, /s/+stop clusters, and voiceless stops with significantly different VOT values. These should be produced with lead voicing, short-lag voicing, and long-lag voicing respectively.

3) When compared to adult values, the VOT values of the children's /s/+stop clusters will be more adult-like than their voiced or voiceless stops.

The third hypothesis was based on the assumption that the short-lag stop in the /s/+stop clusters develop earlier than the lead voicing of voiced stops or the long-lag voicing of voiceless stops. Therefore the children are expected to be closer to mastery of these stops as evidenced by more adult-like VOT means and ranges.

Methods

This experiment compared VOT values in the production of voiced stops, /s/+stops, and voiceless stops in the speech of English-speaking adults and 4-year-old children.

Participants

Adults. Thirty monolingual English speaking adults, including 15 males and 15 females, participated in the experiment. The adults were screened using the following criteria for inclusion: (a) 18-45 years of age, (b) a history of typical hearing as reported by the participant, (c) monolingual English speakers, (d) no history of speech disorder, and (e) grew up speaking and continuing to speak with an accent characteristic of the Western United States.

Children. The children's speech samples were previously gathered independently as monolingual controls in an ongoing investigation of bilingual speech development (Gildersleeve-Neumann, In Progress). The children were recruited from Head Start programs throughout the Portland, Oregon, metropolitan area. All of the children included in this investigation passed a screening for typical hearing, speech, and language development.

Speech samples of 43 monolingual English-speaking children between the ages of 4;0 and 5;0 were originally included in this investigation. Future research may include 3-year-olds and 5-year-olds as more samples become available. VOT from 4 children were not included because the children produced the majority of /s/+stop clusters as single stops. An additional sample was not included because VOT values could not be obtained for the child's productions of voiced stops. This child placed the words in phrases like "a bike" with continuous voicing between "a" and the voiced stop. The remaining 37 children were subdivided into two groups, a younger group and an older group as shown in Table 5 to look for evidence of developmental changes in VOT values. Attempts were made to keep the numbers of male and female children in each age group consistent to control for gender.

Table 5

Demographics of Participating Children

	Younger Children	**Older Children**
Age	4;0 – 4;6	4;7 – 4;11
Number of Participants	17	20
Gender	6 Males 11 Females	10 Males 10 Females
Mean Age (standard deviation)	4;4 (1.4 months)	4;8 (1.5 months)

Stimuli

The children's speech samples were gathered as part of an ongoing investigation that began in 2004. Samples gathered early in that investigation included the stimulus words shown in Table 6. The stimuli were modified in 2005 to include different words also shown in Table 6. The stimulus words were randomly embedded in a 100 word picture naming task. The stimulus words were designed using the following criteria: a) easily identifiable by children, b) in the initial position of the stressed syllable, and c) words within a set contain vowels produced with similar tongue position. Adult speech samples were gathered using the latter set of stimulus words in Table 6.

Table 6

Stimulus Words

2004 stimulus words			
	Voiced	/s/+stop cluster	Voiceless
Bilabial	big	Spider	pig
Alveolar	dog	Stars	tongue
Velar	girl	School	cookies
Fall 2005 - Present Stimulus words			
	Voiced	/s/+stop cluster	Voiceless
Bilabial Set #1	boot	Spoon	pool
Bilabial Set #2	bike	Spider	pie
Alveolar Set #1	door	Stars	toe
Alveolar Set #2	dog	Stop	tongue
Velar Set #1	goose	School	cookies
Velar Set #2	gate	Skate	cake

VOT values were not obtained for every stimulus word for every child. The number of VOT values gathered for each word is shown in Table 7. Reasons why VOT values were not obtained include: the word was not elicited, background noise interfered with reading spectrograms and waveforms, and children put the word in a phrase like "a dog" and continued voicing between words. Many children put the words into phrases like "those are iceskates" or "a birthdaycake". These samples were included if the new production did not interfere with the ability to read VOT values. In some instances, non-stimulus words were used as replacement words for stimulus words that were not elicited or were unreadable. These words and the number of productions used are also shown in Table 7.

Table 7

Number of VOT Values Recorded for Each Word by Age Group

Word	Number of VOT values obtained from Adults	Number of VOT values obtained from older children	Number of VOT values obtained from younger children
Boot	30	15	9
Bike	30	13	9
Big	-	3	6
Bird	-	2	1
Books	-	-	1
Boy	-	-	1
Spider	30	20	16
Spoon	30	14	9
Pie	30	14	10
Pool	30	14	10
Pig	-	5	7
Door	30	12	10
Dog	30	19	16
Stop	30	14	9
Stars	30	18	17
Tongue	30	20	16
Toe	30	13	8
Toys	-	2	2
Goose	30	12	6
Gate	30	14	10
Girl	-	2	8
School	30	19	15
Skate	30	15	10
Cookies	30	20	14
Cake	30	15	9
Kid	-	-	1
Cars	-	-	1

Procedures

Children's speech samples were collected at Head Start facilities in the least distracting environment possible. The speech samples were elicited by speech-language pathology graduate students trained in the picture naming task. When a child did not know the name of a picture, a delayed imitation procedure was used; if unsuccessful, the particular item was not elicited.

The adult speech samples were collected in a quiet research room at Portland State University. Adult's read 1 of 5 randomized word lists, containing 50 total words. The adult's were instructed to pause after every 10 words during which they were asked questions about their experiences with other languages and accents. Each list was read by 3 males and 3 females for a total of 30 samples. VOT values were obtained for every production as shown in Table 7.

Speech samples were either recorded on a Tascam DA-P1 digital audio tape recorder with a table top Sennheiser microphone or with an Edirol R-01 digital audio recorder with an internal microphone. Waveforms and wide band spectrograms of each target word were generated and analyzed using Praat, Version 4.5.15. Waveforms graph changes in air pressure over time and spectrograms provide visual representation of three acoustic features including, time, frequency and intensity.

Measurements

Voice onset time (VOT) values were measured from waveforms and spectrograms generated from the speech samples. VOT was measured as the difference between two points, release of the stop and onset of voicing. Longer segments of speech showing a whole word were used to mark the approximate locations of the release of the stop and onset of voicing. Measurements were adjusted using shorter segments of speech. Release of the stop is represented on spectrograms as a vertical line of energy and as a change in pressure on the waveform. Onset of voicing is illustrated on the spectrogram by a bar of low frequency energy and by the onset of periodic pressure changes on waveforms. These measurements are illustrated in Figure 1. For the purposes of this study, the release of the stop was set as the zero point along the VOT continuum such that instances of lead voicing are represented by negative values.

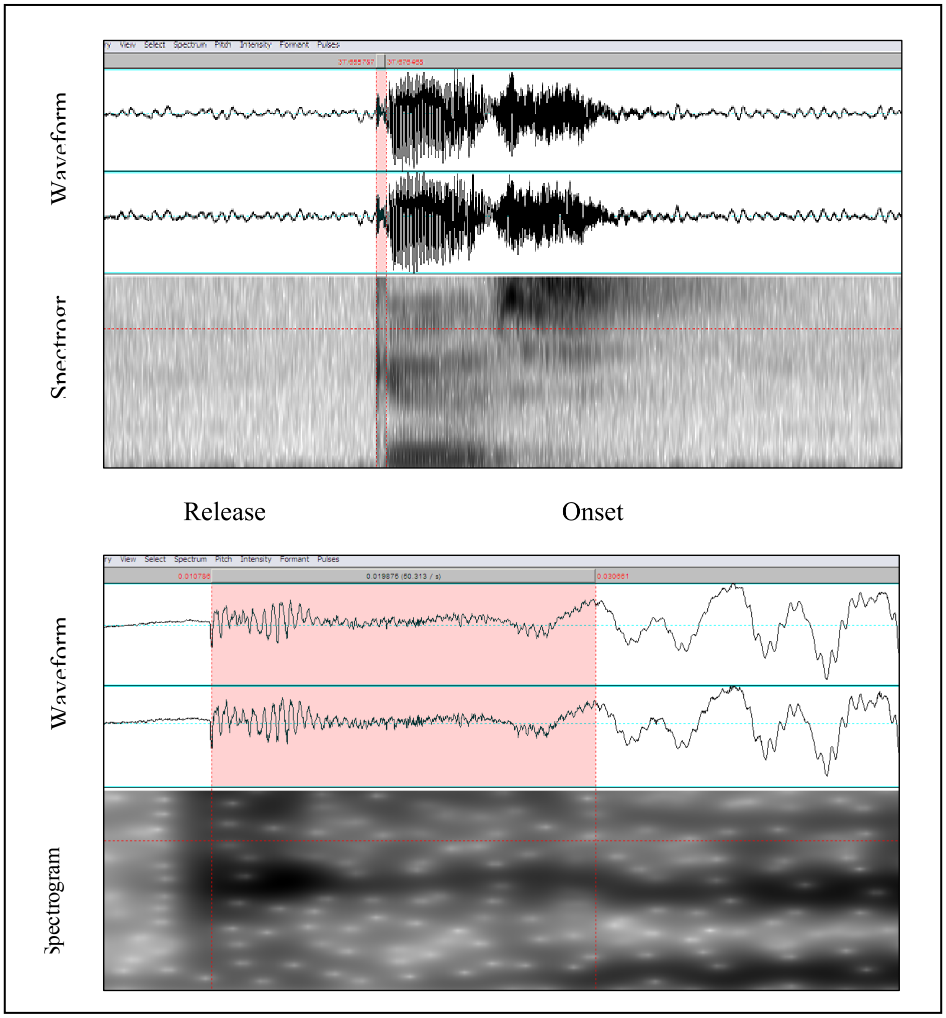

Figure 1. Example VOT measurements for the word “goose”. The top picture illustrates waveform and spectrogram of the entire word with the approximate locations of release of the stop and onset of voicing marked. The bottom picture is of the same spectrogram and waveform with the view zoomed in on the interval between the release of the stop and onset of voicing.

Experimental Design

This experiment examined the effects of three independent variables including age, voicing category, and place of articulation on one dependent variable, VOT. The independent variables were divided into the following categories:

1) Age: adults, older children (4;7-4;11), and younger children (4;0-4;6).

2) Voicing category: voiced, /s/+stops, voiceless.

3) Place of articulation: bilabial, alveolar and velar.

Statistical analyses were completed using SPSS version 15.0. Tests of between subject effects were performed using four ANOVA analyses. The first analyses were conducted using the full sample with age, voicing, and place as factors. Separate ANOVA analyses were conducted for each age group with voicing and place as factors. A significance level of $p < .05$ was adopted. Visual comparisons of VOT means, ranges, and distributions were made between age groups, voicing, and place categories.

Reliability

Reliability was demonstrated as a correlation between two raters. Ten percent of the samples were randomly selected and measured by the second rater, including an equal percentage of samples from adults and children. Inter-rater correlation was high at $r = .951$. The mean of the absolute differences between raters was 5.29($\pm$2.76) milliseconds.

Results

A mixed linear model ANOVA was performed on the full sample of participants using the following factors: place (bilabial, alveolar, velar), voicing (voiced, /s/+stop, voiceless), and age (adults, older children, younger children). The results show that VOT values for the full sample were significantly affected by voicing category [F(2, 4.055) = 61.211, p = 0.001, η_p^2 = 0.968]. VOT values were not significantly affected by place [F(2,4.223) = 4.145, p = .101, η_p^2 = .663] or age [F(2,4.758) = 0.41, p = 0.685, η_p^2 = 0.147]. Additionally, the results show a significant interaction between place and voicing [F(4, 1046) = 6.302, p = 0.000, η_p^2 = 0.024], suggesting that the voicing category has differing effects on VOT values depending on the place of articulation. The interaction between age and voicing category was also significant [F(4, 1046) = 7.98, p = 0.000, η_p^2.= 0.03]. This significant interaction suggests that the voicing category has differing effects on VOT values depending on a person's age. The interaction between place and age was not significant [F(4, 1046) = 1.99, p = 0.094, η_p^2 = 0.008].

In order to explore the voicing factor within each age group, a factorial ANOVA was conducted for each age group using place and voicing category as factors. The analyses revealed a significant effect for voicing in each age group including adults [F(2) = 397.211 , p = .000, η_p^2 = .599], older children [F(2) = 124.543, p = .000, η_p^2 = .466], and younger children [F(2) = 85.278, p = .000, η_p^2= .436]. These finding suggest that each age group produced voiced stops, /s/+stops, and voiceless stops with significantly different VOT values. The effect of place was significant for the younger children [F(2) = 5.759, p = .004, η_p^2= 0.050], but not for the adults [F(2) = 1.390, p = .250, η_p^2= 0.005] or the older children [F(2) = 1.997, p = .138, η_p^2= 0.014]. There was a significant interaction between voicing and place for the younger children [F(4) = 2.440, p = .048, η_p^2= 0.042], and the adults [F(4) = 4.618, p = .001, η_p^2 = 0.034], but not for the older children [F(4) = 1.949, p = .102, η_p^2 = 0.027].

Following each ANOVA, Post-hoc Tukey HSD *t* tests were conducted to make comparisons between the voicing categories within an age group. These tests revealed that all three age groups made significant distinctions between the three voicing categories. These results are shown in Table 8.

Table 8

Post-hoc Tukey HSD t Tests: Comparisons between Voicing Categories

	Significance		
Comparison	**Analysis for adults**	**Analysis for older children**	**Analysis for younger children**
Voiced vs. /s/+stops	0.000	0.000	0.008
/s/+stops vs. Voiceless	0.000	0.000	0.000
Voiced vs. Voiceless	0.000	0.000	0.000

Estimated Marginal Means from the full sample were used to make visual comparisons of the voicing categories between the age groups, and places of articulation. Place was included in these analyses to explore the interaction between voicing category and place. The mean VOT values and 95% confidence intervals are presented in Appendix A and Figure 2. The figure shows that /s/+stops and voiceless stops were produced with similar VOT values in all three age groups. Voiced stops, however, were produced with different VOT values in each group. The most dramatic contrast between age groups occurred for the velar voiced stops.

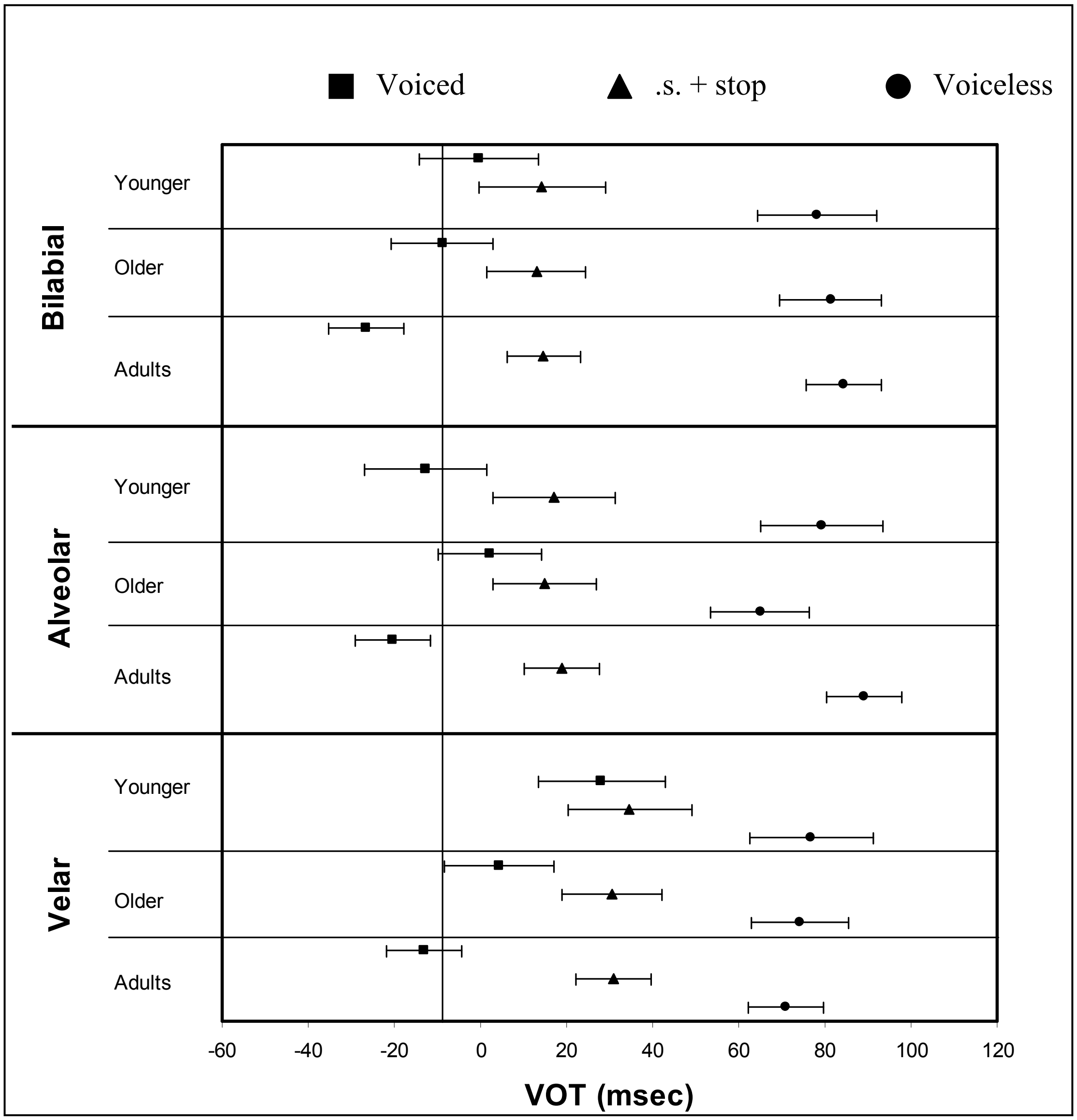

Figure 2. Estimated Marginal Means of VOT values by voicing category, place, and age group for the Full Sample with 95% Confidence Intervals.

The figure in Appendix B shows the VOT values of every stop analyzed and thus illustrates the range of VOT values produced in each voicing category by each age group. This figure is also divided by place to explore the interaction between place and voicing. Both groups of children appear to have a larger range of VOT values for voiceless stops than the adults. The range of /s/ + stops VOT values also appears slightly larger in the children's group than the adult group. Surprisingly, the children's voiced stops appear to occur within a range of VOT values similar to adults. Initially, this observation seems contrary to the developmental changes shown in Figure 2.

Another way to view Appendix B is to look at the distributions of the stops produced. A visual comparison reveals that adults produced a greater percentage of voiced stops with lead voicing. Based on this observation, the percentage of voiced stops produced with lead voicing was calculated and is presented in Table 9. The calculations show that younger children produced the lowest percentage of voiced stops with lead voicing. Lead voicing occurred slightly more frequently in the older children's productions, and adults produced the greatest percentage of voiced stops with lead voicing. As with the means presented in Figure 2, the most dramatic increase occurred for the velar voiced stops.

Table 9

Percent of Voiced Stops Produced with Lead Voicing in Each Age Group

	Bilabial	**Alveolar**	**Velar**	**Total**
Adults	41.67%	36.67%	36.67%	38.33%
Older children	21.21%	16.13%	14.29%	17.39%
Younger children	18.52%	15.38%	4.17%	12.99%

During data collection, the children produced 15 reduced clusters that yielded VOT values. These productions were not included in the above statistical analyses, but are represented visually in Figure 3. The majority of the reduced clusters were produced with short-lag VOT values similar to other children's /s/+stop clusters. However, the resulting stops could also be described as similar to the other children's voiced stops since the children produced voiced stops with both short-lag and lead voicing. Figure 3 provides a visual comparison between the reduced stops, voiced stops, and voiceless stops for the individual children who produced them. Out of 15 productions, 9 of the reduced clusters were produced with VOT values similar to the corresponding voiced stops, 1 was produced with VOT similar to the corresponding voiceless stops, and 5 were produced with unique VOT values.

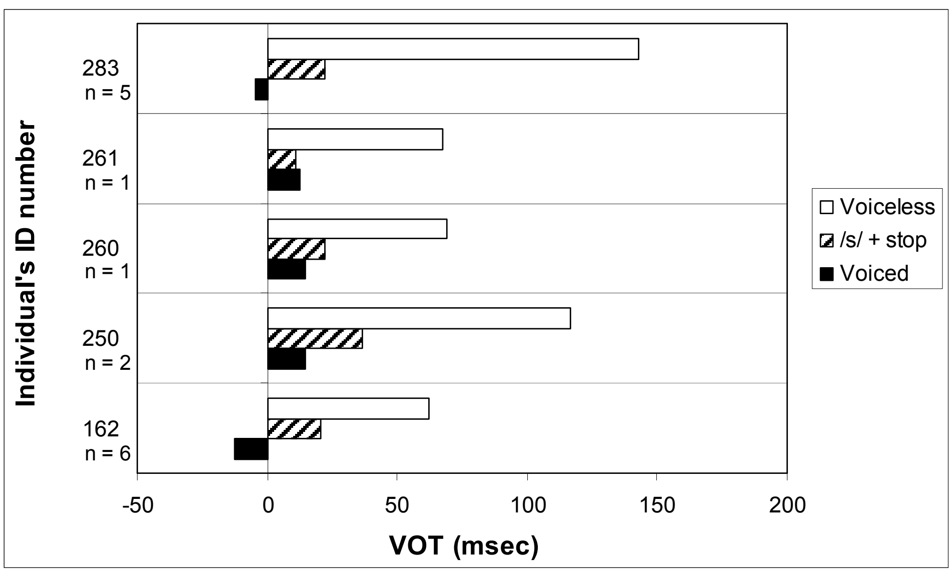

Figure 3. VOT values of reduced /s/+stop clusters and voiced and voiceless stops in the same word set (see Table 6) by individual participant. n represents the number of word sets produced with a reduced cluster by that individual child.

Discussion

In this study, comparisons were made between VOT values of voiced stops, /s/+stops, and voiceless stops in the speech of adults and 4-year-old children. The results indicate that when lead voicing is included in the analyses, VOT values for voiced stops and /s/+stops are different. The results also suggest that 4-year-old English-speaking children are still in the process of developing adult-like VOT values for voiced stops with older children having more adult-like productions than younger children. The most dramatic developmental changes occurred for the velar voiced stops. The children produced voiceless stops with adult like means, but wider distributions of VOT values. When the means, ranges, and distributions are all considered it appears that the children's most adult-like VOT values occurred for productions of /s/+stops.

The analyses support the first two hypotheses that adults and 4-year-old English speaking children produce voiced stops, /s/+stops, and voiceless stops with significantly different VOT values. Previous studies comparing VOT of /s/+stops, with voiced and voiceless stops in English-speaking adults and children have concluded that /s/+stops are produced with VOT values resembling voiced stops. However, these studies did not include lead voicing. The results presented here indicate that when lead voicing is included, voiced stops and /s/+stops should not be described as having similar VOT values.

As predicted, all of the age groups produced voiceless stops with long-lag voicing and /s/+stops with short-lag voicing. The adults and older children produced voiced stops with means in the lead voicing category; however, the older children's mean was close to zero. An unexpected finding was that the younger children's mean for voiced stops occurred in the short-lag voicing category. This finding will be explored during discussion of the third hypothesis.

The third hypothesis made a prediction about the maturity of children's voicing contrasts as follows: when compared to adult values, the VOT values of the children's /s/+stop clusters will be more adult-like than their voiced or voiceless stops. This hypothesis was based on previous research indicating that short-lag stops are easier to produce and therefore develop earlier in children's speech. In order to look for changes in VOT during development, the children were divided into two groups, an older group and a younger group. Visual comparisons of means, ranges, and distributions were made between the age groups for each voicing category.

Looking at the means, it appears that all three age groups produced /s/+stops with similar VOT values, and voiceless stops with similar VOT values. This indicates that even the younger children have established adult-like VOT for /s/+stops and voiceless stops. In contrast, voiced stops were produced with different means by each age group. Contrary to previous research on VOT development, this suggests that 4-year-old children are still in the process of developing adult-like voiced stops, with velar stops changing most dramatically.

Visual comparisons were also made between the ranges of VOT values. These comparisons suggest that the children's voiced stops were produced with a range of values most similar to the adult's range. This is counter to the comparison made between the means which implied that the children's voiced stops were the least adult-like. This contrast is explained by examining the distribution of values, specifically, the percentage of voiced stops that are produced with lead voicing. The adults produced a larger percentage of voiced stops with lead voicing than the children. Furthermore, the older children produced a larger percentage of voiced stops with lead voicing than the younger children. These findings imply that 4-year-old's continued development of VOT for voiced stops, especially velar voiced stops, primarily results from producing an increasing percentage of voiced stops with lead voicing.

The dramatic changes observed for velar voiced stops are consistent with normal speech sound development. Velar sounds normally develop later than bilabial and alveolar sounds, which may be produced for velar sounds during speech development. When viewed from an articulatory theoretical perspective of speech development, the changes observed in this study would imply that of all the sounds investigated, velar voiced sounds are the most difficult to produce.

This study also used visual comparisons to examine productions of reduced clusters. Reduced clusters were compared within an individual to voiced and voiceless stops within a word set (see Table 6). This was done to examine if children who reduced clusters produced stops with VOT values equivalent to their voiced stops, voiceless stops, or with unique VOT values equivalent to the stops within mature /s/ + stop clusters. The results suggest that children are not necessarily reducing clusters to voiced or voiceless stops as had been suggested in previous studies. Instead, it appears that at least some children are producing unique stops equivalent to the stop within mature clusters. This is evidenced by children who used lead voicing for voiced stops, short-lag voicing for the reduced cluster, and long-lag voicing for voiceless stops. This suggests that the children perceive a distinction between voiced stops, /s/+stops, and voiceless stops, and that they are replicating that distinction in their productions. This finding supports the physiologically based theory of VOT development adopted by this investigation.

This study is limited by the context in which the stops were produced. The experiment was designed to elicit productions of stops in single words by both the children and the adults. However, many of the children put the words into compound words or phrases such as "iceskates" or "it's a stop sign." These productions are more similar to spontaneous speech than the adult productions. The different contexts could have created a discrepancy in the level of enunciation between the age groups. Additionally, differing vocabularies, and abilities to attend to the task may have resulted in the adults enunciating the words more than the children. Increased enunciation may have led to an increased use of lead voicing. Previous studies that have included lead voicing also examined stops in single words. Future research should investigate the use of lead voicing in spontaneous speech samples.

Additional research should be conducted to confirm older children's continued development of voiced stops. VOT measurements from 3-year-olds, 5-year-olds, and older children should be examined for additional support of the developmental pattern demonstrated by these results. Additionally, a longitudinal study of VOT development could examine developmental changes within individuals. Studies involving 3-year-olds would also provide more instances of reduced clusters for examination. Finally, the implication that older children are still developing voiced stops should be considered during future investigations of VOT development in bilingual speakers and children with disordered speech.

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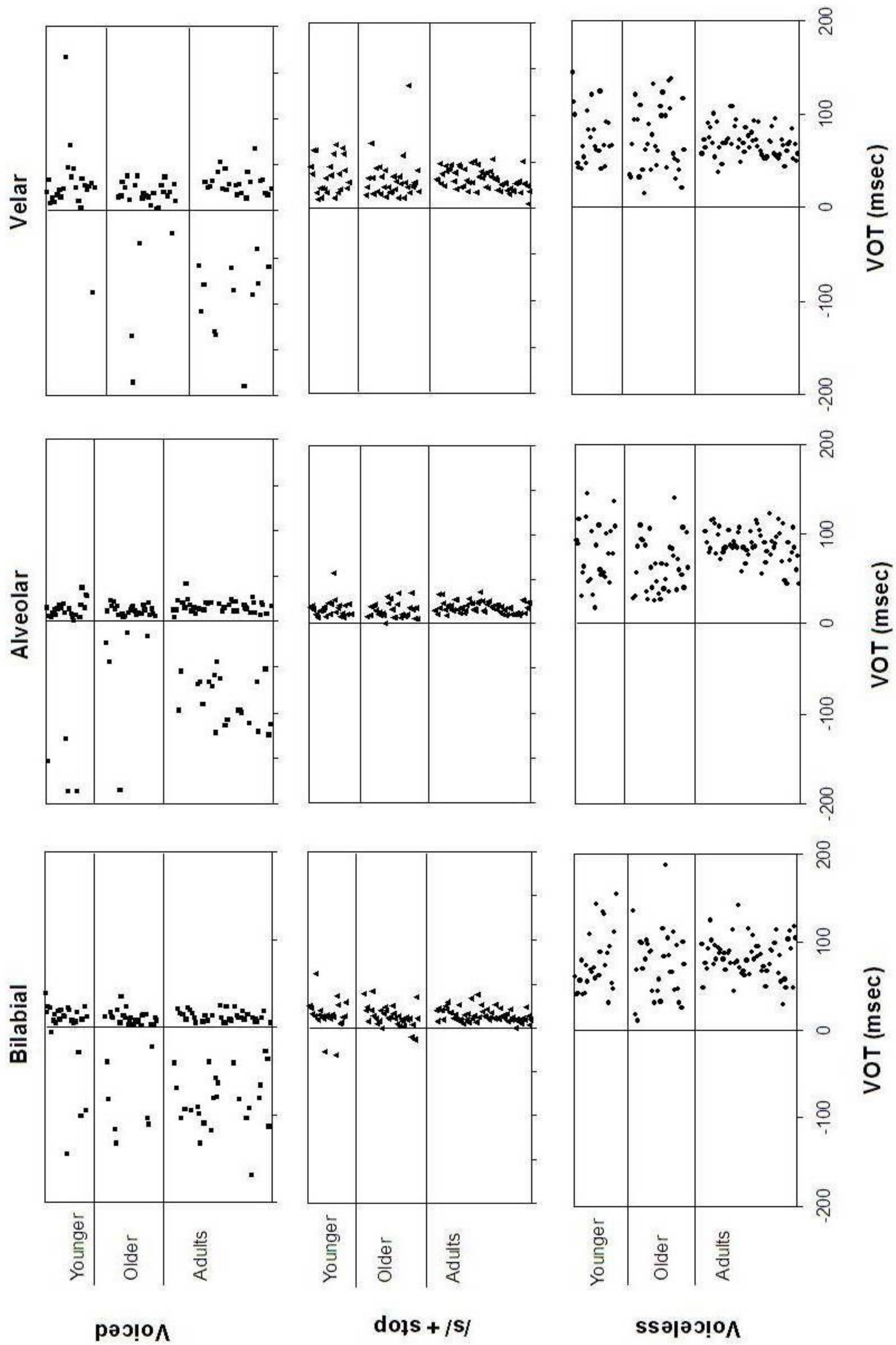
APPENDIX A

Estimated Marginal Means (age*voicing) for the Full Sample.

Age Group	Voicing Category	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
Adults	Voiced	-19.978	2.593	-25.066	-14.889
	/s/+stop	21.572	2.593	16.483	26.660
	voiceless	81.424	2.593	76.335	86.512
Older Children	Voiced	-0.604	3.631	-7.730	6.521
	/s/+stop	19.457	3.480	12.629	26.286
	voiceless	73.431	3.429	66.703	80.160
Younger Children	Voiced	4.864	3.967	-2.921	12.648
	/s/+stop	22.112	4.018	14.227	29.997
	voiceless	78.110	3.967	70.378	85.842

APPENDIX B

VOT values by voicing category and age group for all productions analyzed.



APPENDIX C

Recruitment Flyer – Adults

Whether it is to…

further KNOWLEDGE,

Help us better understand speech development in monolingual and bilingual children.

build KARMA,

The study will also help fulfill a requirement for the researcher's completion of a master's degree. Remember….you may need to recruit people in the future….and what better way to build recruiting karma or karma in general than through participating.

or for a chance to WIN…

Now I've got your attention. When you participate you will be entered in a drawing for a $25 gift certificate to Starbucks. With two convenient locations adjacent to campus and winter around the corner….guilt free lattes could be yours.

please PARTICIPATE

What do I have to do?

This study is investigating specific speech sounds in the English language. If you decide to participate you will asked to name a series of easily identifiable pictures into a microphone. Your speech will be recorded and analyzed. You will also be asked to fill out a short questionnaire regarding your language history. The whole process should take approximately 15 minutes.

We are seeking participants who are (1) 18-45 years of age, (2) have a history of typical hearing as reported by the participant, (3) monolingual English speakers (4) native to Oregon or have lived in Oregon for 5+ years.

To find out more, ask questions or if you are interested in participating, please call (970-281-9022) or send me an email (jenweber@yahoo.com).

APPENDIX D

Adult Consent Form

Voice Onset Time of Initial Stop Consonants of Monolingual English Speaking Adults

You are invited to participate in a research study conducted by Jennifer Weber from Portland State University, Department of Speech and Hearing Sciences. The goal of the study is to establish normative data for adult speakers of English to be used in the investigation of speech development. The study will also help fulfill a requirement for the researcher's completion of a master's degree. Research will be conducted under the supervision of Dr. Gildersleeve-Neumann, Ph.D., CCC-SLP at Portland State University, Department of Speech and Hearing Sciences. You were selected as a possible participant in the study because you are (1) 18-45 years of age, (2) a history of typical hearing as reported by the participant, (3) monolingual English speakers, (4) no history of speech disorder, (5) grew up speaking and continue to speak with an accent characteristic of the Western United States.

If you decide to participate, you will be asked to answer a few questions about your own language background including your exposure to languages other than English as well as regional and cultural dialects and accents. These questions will take approximately 5 minutes. You will then be asked to say a list of 50 words while speaking into a recorder. Your voice will be recorded and the acoustic features analyzed to be used in a study of speech development. The task should take approximately 10 minutes. These procedures will be completed at the Speech and Hearing Sciences Department at Portland State University. Participating in this study will require you to donate approximately 15 minutes of your time and a recorded sample of your speech. Before recording you will be provided with a brief explanation of the equipment and the purpose of the study. Any questions you have will be welcome and answered to the best of the researches ability. Your participation is voluntary. If at anytime you are uncomfortable you may discontinue and it will not affect your course grade or your relationship with the researchers involved and/or the Speech and Hearing Sciences Department at Portland State University. While there may be no direct compensation, your participation may help to increase knowledge about speech development which may help teachers and other professionals better serve children.

Any information that is obtained in connection with this study that can be linked to you or identify will be kept confidential. This means that the names of people who take part in the study will not be given to anyone else. No one other than the researcher and supervisor will have access to the information. The audiotapes and written records will be stored in a locked file cabinet at Portland State University. Information collected from participants will be used for research purposes only.

If you have concerns or problems about your participation in this study or your rights as a research subject, please contact the Human Subjects Research Review Committee, Office of Research and Sponsored Projects, 111 Cramer Hall, Portland State University, (503) 725-4288. If you have questions about the study itself, contact Jennifer Weber by email at jenweber@yahoo.com or by mail at the Speech and Hearing Sciences Department, Portland State University, PO Box 751, Portland, OR 97207 or by phone at (970) 281-9022.

Your signature indicates that you have read and understand the above information and agree to take part in this study. Please understand that you may withdraw your consent at any time without penalty, and that, by signing, you are not waiving any legal claims, rights or remedies. The researcher should provide you with a copy of this form for your own records.

____

Signature Date

APPENDIX E

Adult Language Questionnaire

Thank you for choosing to participate in this study. We are seeking to establish normative information for speech sounds used in English. To do this we are interested in gathering data from monolingual English speaking adults in the Portland area. This short questionnaire will ask you about your language exposure and proficiency.

1. How long have you lived in Oregon?
2. Do you consider yourself to have an accent or speak a dialect different than the standard for Portland, Oregon?
3. Have you previously had an accent or spoken a dialect different than the standard for Portland, Oregon? Please describe.
4. Are you a native English speaker?
5. Do you speak any other languages?
6. Please describe your exposure to any language you speak other than English.
    a. At what age did you learn the other language?
    b. Did you study another language in school?
    c. How many years did you study that language?
    d. On a scale from 0 (not a word) to 10 (native like speaker), how would you rate your proficiency in another language?
7. Do you have a known hearing loss or has your hearing ever been impaired?
8. Have you ever received treatment for a speech or language disorder?