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Acoustic Cue Weighting in Children Wearing Cochlear Implants

Junghwa Bahng
University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a dissertation written by Junghwa Bahng entitled "Acoustic Cue Weighting in Children Wearing Cochlear Implants." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in .

Mark S. Hedrick, Major Professor

We have read this dissertation and recommend its acceptance:

Deborah von Hapsburg, Ashley W. Harkrider, Mary Sue Younger

Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Acoustic Cue Weighting in Children Wearing Cochlear Implants

A Dissertation
Presented for the
Doctor of Philosophy Degree
The University of Tennessee, Knoxville

Junghwa Bahng
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Abstract

The purpose of this study was to determine how normal hearing adults (NHA), normal hearing children (NHC) and children wearing cochlear implants (CI) differ in the perceptual weight given cues for fricative consonant and voiceless stop consonant continua. Ten normal-hearing adults (NHA), eleven 5-8-year-old normal-hearing children (NHC) and eight 5-8-year-old children wearing cochlear implants (CI) were participants. For fricative consonant perception, the /su/-/ʃu/ continua were constructed by varying a fricative spectrum cue in three steps and by varying a F2 onset transition cue in three steps. For voiceless stop consonant perception, the /pu/-/tu/ continua were constructed by varying a burst cue in three steps and a F2 onset transition cue in three steps. A quantitative method of analysis (ANOVA model) was used to determine cue weighting and measure cue interaction. For the fricative consonant, both NHC and NHA gave more perceptual weight to the frication spectral cue than to the formant transition. NHC gave significantly less weight to the fricative spectrum cue than NHA. The weight given the transition cue was similar for NHC and NHA, and the degree of cue interaction was similar between two groups. The CI group gave more perceptual weight to the fricative spectrum cue than to the transition. The degree of cue interaction was not significant for CI. For the voiceless stop consonant, both NHC and NHA gave more perceptual weight to the transition cue than to the burst cue. NHC gave proportionately less weight to the transition cue than NHA. The weight given the burst cue and the degree of cue interaction were similar between NHC and NHA. The CI group gave more perceptual weight to the transition cue than to the burst cue, and there was no significant difference between children wearing cochlear implants and normal hearing children group; however, the degree of cue interaction was not significant for CI. These results indicated that all groups favored the longer-duration cue to make phonemic judgments. Also there were developmental patterns. The CI group has similar cue weighting strategies to age-matched NHC, but the integration of the cues was not significant for either fricative or voiceless stop consonant perception.

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CHAPTER I

INTRODUCTION

Cue weighting is perceptual attention given to the various cues used during the process of speech perception (Nittrouer & Crowther, 1998). Individuals give different perceptual weight to acoustic cues, and the weighting strategies of children are significantly different from those of adults. The periphera l auditory system is not responsible for the perceptual differences between children and adults because the cochlea is already mature at birth (Sussman, 2001). There are two general hypotheses that attempt to explain the differences between speech cue weighting strategies of children and adults. However, there is no consensus regarding why and how these differences exist.

One of the earliest studies to compare the speech perceptual abilities of children and adults was conducted by Morrongiello and her colleagues (Morrongiello, Robson, Best, & Clifton, 1984). They examined the perceptual "trading relation" in stop-consonant perception. In a trading relation, the value of one acoustic cue is enhanced, while the value of another acoustic cue is decreased for the same phonetic contrast perception. That is, two or more cues are integrated, but the weights are different for different cues. In this study, the magnitude of the trading between a spectral cue (F1 onset frequency) and a temporal cue (silence duration) was less for children than adults. Morrongiello et al. concluded that children and adults gave different perceptual weights to the two cues.

Based on the work of Morrongiello et al., Nittrouer and colleagues (Nittrouer, 1992; Nittrouer, 1996; Nittrouer, Manning, & Meyer, 1993; Nittrouer & Miller, 1997) proposed the Developmental Weighting Shift (DWS) hypothesis. This hypothesis states that young children use acoustic cues differently than adults in order to achieve the same perceptual goals, and that children generally learn to weight segments in an adult-like manner as they gain more language experience. According to the DWS hypothesis, transition cues provide children with more information than steady-state cues as they endeavor to identify the consonants in the /s/-/ʃ/ continua (Nittrouer, 1992; Nittrouer & Miller, 1997). Transition cues are associated with vocal-tract movement and changing acoustical signals from a consonant to a vowel in CV syllables over time, suggesting younger children might attend more to the dynamic than the static properties in a syllable (Nittrouer, 1992).

In contrast to the DWS hypothesis, Sussman (2001) suggested that auditory sensitivity to acoustic parameters affects linguistic decisions. The immature cortical auditory sensitivity of younger children leads them to have different speech cue weighting strategies than adults. This hypothesis can explain how children depend on speech cues that are either louder or of longer duration (Ohde & Haley, 1997; Sussman, 2001), or contain more extensive spectral information (Dorman, Loizou, Kirk & Svirsky, 1998; Eisenberg, Shannon, Martinez, Wygonski, & Boothroyd, 2000). One recent study by Sussman (2001) showed that children weight longer and louder cues (such as steady-state cues) more than dynamic cues (such as transition cues) when perceiving vowels.

Due to the differences in methodologies used in prior research (i.e., the different ages of the subjects, different stimuli, and different manipulated cues), there is no consensus regarding perceptual strategies used by younger children. Moreover, there have been few studies of the perceptual development of hearing-impaired children.

Hearing-impaired children have limited audibility, less language experience, and they experience distorted sound relative to normal hearing children (Carney & Moeller, 1998). As a result they may have different speech cue weighting strategies than normal-hearing children. The overall goal of this study is to determine the speech cue weighing strategies of hearing-impaired children, particularly those who use cochlear implants.

CHAPTER II

REVIEW OF LITERATURE

Fricative Consonant Perception

Normal-hearing Listeners

The perception of fricative consonant place of articulation derives from the frequency-specific noise spectrum cue and the second formant transition cue appropriate to the vowel environment (Harris, 1958). Research investigating perception of fricative consonants has indicated that children and adults use different cue weighting strategies. More specifically, young children tend to give more weight to dynamic cues (such as formant transitions) and less weight to cues that are relatively static (such as frication noise) (Nittrouer, 1992, 1996, 2002; Nittrouer & Miller, 1997). In Nittrouer's (1996) study, 3-year-old children were assessed for the ability to label fricative noise consonants in the /s/ to /ʃ/ continua in /u/ and /a/ environments. The results revealed that children are not as sensitive as adults in distinguishing acoustic features in fricative noise-vowel continua, although fricative consonants have relatively long durations of noise (Kent & Read, 2001). Nittrouer (2002) also investigated the cue weighting differences between adults and children 4, 6, and 8 years of age by using natural fricative noise, /s/-/ʃ/ and /f/-/Ɵ/ continua, with synthetic vowel portion. The frequency of F2 was manipulated in nine steps. The results indicated that children and adults use similar perceptual weighting strategies for fricative noise spectrum cues and formant transition cues in the /f/ versus /Ɵ/ vowel syllable continua. This is in contrast to previous studies that have revealed different cue weighting strategies in the /s/ versus /ʃ/ continua. The results revealed that children had mature speech cue weighting strategy in the /f/-/Ɵ/ syllable continua. In the

/s/ - /ʃ/ continua experiment, children significantly focused more on transition cues and less on fricatives than adults. In the results, children and adults used more transition cues than frication noise for identification of stimuli. As children acquire increased language experience, the amount of weighting on spectrum cues in the sibilant (/s/-/ʃ/) contrast also increases with a corresponding decrease in the weight assigned to formant transition cues. That is, perceptual strategy is modified with increasing language experience. This is the basis for the Developmental Weighting Hypothesis (DWS) (Nittrouer, 1997, 2002).

Hedrick, Bahng, and von Hapsburg (submitted) investigated speech cue weighting strategy in perceiving fricative noise spectrum continua in children 4:9~8:8 years old and adults with normal hearing in terms of DWS. Synthetic CV continua representing /su/ and /ʃu/ syllables were used. The poles of the frication noise frequency spectrum varied in 250 Hz steps, from 2200Hz (most /ʃ/-like) to 3700Hz (most/s/-like). The second formant frequency onset was either 1200 Hz (appropriate for /s/) or 1800 Hz (appropriate for /ʃ/). The results showed that there were no differences in weighting on the F2 transition cue in children and adults. In this study, perceptual weights given to the transition and spectrum cues were calculated using an ANOVA model (Hedrick & Younger, 2001, 2003, 2007). In this model, the weights are also referred to as coefficients of determination. The results indicated that of the total weight assigned to cues by adults, spectrum noise cues accounted for 86% of weighting, transition cues for 7%, and integration cues for 4%. Children assigned 50% weight to spectrum noise cues, 9% to transition cues, and 6% to integration cues. The groups differed in the extent of weighting on spectrum cues, but weighting on transition cues did not different. This result suggests that with increasing age, the degree of weighing on spectrum cues increases, but it does not change for transition cues. In a study by Nittrouer (2002), a partial correlation coefficient was used for calculating each cue weight. Results from just one set of continua, which are similar to the continua in Hedrick et al. (submitted), showed that the fricative spectrum cue effects increase and the transition cue effects decrease with increasing age. The results of the two studies demonstrated consistency of fricative spectrum cue effects, but discrepancy of transition cue effects. This may be due to different stimuli manipulations and different statistical analysis methods between the two studies. Earlier studies by Nittrouer and colleagues measured phonemic boundaries for fricative perception and slopes of labeling functions for transition cue effects in adults and children. This method cannot identify the primary cue for identification stimuli or what percentage of each cue weighting was present in each group. Thus, in one study (Nittrouer, 2002), linear regression analyses followed by partial correlation coefficient calculations were performed to determine individual cue weights. However, this method did not provide the proportion of weight assigned to each cue. Second, Nittrouer and colleagues used hybrid stimuli in several experiments. Hybrid stimuli consisted of natural and synthetic portions, whereas Hedrick et al. used synthesized stimuli. These differences may lead to different results between studies.

Summary

In terms of DWS, children attend more to dynamic cues (F2 formant transition cues) and are less sensitive to steady-state cues (fricative noise spectrum cues) than adults (Nittrouer, 1992). However, a recent study (Hedrick et al., submitted) showed that the degree of weighting on fricative noise spectrum cues was significantly different when comparing younger children and adults; although, the degree of weighting on transition cues was similar.

Hearing-impaired Listeners: Adults

Perception of fricative consonants is problematic for hearing-impaired listeners, because fricative noise cues are of a relatively high frequency, and transition cues are of short duration (Harris, 1958; Heinz & Stevens, 1961). Listeners with hearing impairment find fricative consonant syllables difficult to distinguish (Hedrick & Younger, 2003). Zeng and Turner (1990) suggested that if the audibility of frication is provided to hearing-impaired listeners, the frication portion might be sufficient for identification. Although transition cues are usually audible to hearing-impaired listeners, they do not use them as efficiently as normal-hearing listeners (Zeng & Turner, 1990). Thus, it can be concluded that hearing-impaired listeners have less ability to utilize formant transition cues than listeners with normal hearing. Also, in a study by Hedrick and Younger (2003), listeners with hearing impairment exhibited difficulty in perceiving transition cues. The perceptual weight given formant transition and relative amplitude information for labeling fricative place of articulation and the extent of integration of relative amplitude and formant transition cues were measured in fricative noise consonant /s/- /ʃ/ contrast. The results revealed that normal-hearing listeners and hearing-impaired listeners gave significant different weighting to the second formant (F2) transition and relative amplitude cues. The researchers thought these differences might be related to cue availability or coding. Moreover, voiceless fricative cue weighting or integration might be dependent on frication duration. In addition, listeners with SNHL had lower interaction terms for F2 transition and relative amplitude cues. Taken together, these results support auditory-based theories of speech perception in adults.

Hedrick and Carney (1997) also studied adult listeners wearing cochlear implants and adults with normal hearing. They assessed the effects of relative amplitude cues and formant transitions on perception of place of articulation. Two places of articulation consonant contrasts were used: /s/ - /ʃ/ and /p/ - /t/ continua in the /a/ environment. Results showed that cochlear implant listeners (Nucleus 22, MPEAK strategy) and normal-hearing listeners used different strategies. Listeners wearing a cochlear implant could use relative amplitude to consistently label place of articulation, and listeners with normal hearing integrated the relative amplitude and formant transition information to make phonemic judgments. It might be possible that speech processors are not sensitive to frequency changing in short time, so cochlear implant users have different weighting patterns of transition cues from those of normal hearing listeners.

Summary

Hearing-impaired listeners have difficulty perceiving fricative consonants due to limitations in audibility and the distortion of sounds. Hearing-impaired listeners, hearing-aids users and cochlear implants users, have difficulty integrating static and dynamic cues, unlike normal-hearing listeners.

Hearing-impaired Listeners: Children

Carney and Moeller (1998) suggested that children with SNHL might show evidence of a reduction in both the quality and quantity of speech and language experience. Children with moderate to severe SNHL may use listening strategies that differ from those of children with normal hearing in the same age group (Pittman &

Stelmachowicz, 2000). Pittman and Stelmachowicz (2000) studied the perception of fricative sounds in normal-hearing and hearing-impaired children and adults. Four postvocalic fricative sounds, /s, ʃ, f, Θ/ in the /u/ vowel environment were used. All four listening groups weighted frication for the /us/ and /uʃ/ syllables more heavily than formant transitions. For /uf/, listeners with normal hearing weighted the frication more than the transition, whereas the listeners with hearing loss gave low weights for both frication and transition. For the /uΘ/ syllable, children and adults with hearing loss weighted the fricative noise cue more heavily than normal-hearing children and adults. Thus, except for /uf/, four listening groups gave more weight to fricative noise spectrum cues than to transition cues, finding somewhat contrast to the DWS hypothesis.

In one study by Nittrouer and Burton (2001), mainstreamed children between ages of 8 and 10 with hearing loss showed results similar to those of age-matched children with normal hearing. Non-mainstreamed children with hearing loss, mainstreamed children, and normal-hearing children were compared. The findings from this study showed that normal hearing and mainstreamed hearing impaired children focused more transition cues and less fricative spectrum cues than did adults in fricative consonant continua. Also, there was significantly different cue weighting between non-mainstreamed and mainstreamed children on fricative noise spectrum and transition cue weighting. The results were interpreted to mean that SNHL can result in less experience with perceiving speech and can delay development of mature speech perception and language processing abilities. These deficiencies might be overcome through appropriate early intervention in mainstreamed hearing impaired children.

von Hapsburg, Bahng, and Hedrick (submitted) investigated the speech cue weighting strategies for fricative sounds (/su/ vs. /ʃu/) of children wearing cochlear implants between 5 and 8 years of age. Results for the group of children using hearing aids revealed that they did not consistently label the fricative sounds. Children using cochlear implants did not differ statistically from normal-hearing children in the same age range, but the individual data of cochlear implant groups showed marked variation. Individual variations might be caused by different factors, such as age of implantation or onset of speech/language intervention. However, the researchers did not find any statistically significant factor correlating these variables with that of labeling consistency.

The studies of Nittrouer and Burton (2001), Pittman and Stelmachowicz (2000) and von Hapsuburg et al. (submitted) showed different results. In Pittman & Stelmachowicz, (2000), all children and adults weighted more fricative spectrum cues more than transition cues regardless of hearing sensitivities, and there were no significant differences between children and adults. Also, in von Hapsburg et al. (submitted), normal hearing children and children wearing cochlear implants weighted more fricative spectrum cues more than transition cues; however, Nittrouer and Burton (2001) did not compare two cues within a group. There are some significant differences among the studies. First, three studies used different type of stimuli. Pittman and Stelmachowicz used live voice and vowel-consonant syllables, whereas Nittrouer and Burton used hybrid and consonant-vowel stimuli. Synthesized stimuli were used in the study of von Hapsburg et al. Second, statistical methods were different each other. Pittman and Stelmachowicz calculated cue weighting using correlation coefficients, but Nittrouer and Burton analyzed cue weighting with phonemic boundaries and slopes of labeling function.

Also, von Hapsburg et al. used ANOVA model (Hedrick & Younger, 2001, 2003, 2007) for calculation of each cue weighting.

Stop Consonant Perception

Normal-hearing Listeners: Adults

Stevens and Blumstein (1978) and Blumstein and Stevens (1979, 1980) investigated how the short-term gross spectra shape at consonant release specified the place of articulation in perception of the stop consonant. Stevens and Blumstein (1978) investigated identification of stop consonants [b, d, g] with one of three vowels [i, a, u]. There were three stimulus conditions: burst plus transition, burst only, or formant transition only. The results of this study showed that only the stimulus with burst and formant transition cue and formant transition cue were consistently identified, while stimuli with burst only cue were not consistently identified. These studies suggested that the onset spectra with transition cue is the primary cue in perception of the place of articulation of stop consonants, and burst cue is a secondary cue. Another study by Blumstein and Stevens (1980) concluded that consonant-vowel (CV) stimuli as short as 10-20ms from the onset of the stop consonant were consistently identified for consonantal place of articulation. The results led to the conclusion that the short invariant onset spectra properties have enough information to identify the place of articulation of stop consonants.

On the other hand, Kewley-Port (1983) argued that dynamic changes occur in spectral shape during the initial 20-40 ms of a CV syllable. Following the assumption that a context-free cue should be a static cue, Stevens and Blumstein (1978) suggested that the integrated initial spectrum of the CV could be an invariant cue for the consonant. However, Kewley-Port (1983) proposed that dynamic properties may provide invariant information for identifying consonants and, in particular, burst spectral tilt, VOT, and mid-frequency peaks extending over time are dynamic properties that may provide invariant information for consonant identification. In order to confirm this theory, Kewley-Port, Pisoni and Studdert-Kennedy (1983) used synthetic stimuli patterned either after static cues suggested by Stevens and Blumstein (1978), or dynamic cues suggested by Kewley-Port (1983). The results revealed that listeners more successfully identified the place of articulation of stop consonants that have dynamic properties than those having only static properties.

In addition, Walley and Carrell (1983) compared cue weighting in voiced stop consonants by adults and 5-year-old children. The cues of integration were the onset spectra of the CV, as described by Stevens and Blumstein (1981), and formant transition. In the stimuli, these two cues were in conflict – that is, each cue specified a different place of articulation. The results showed that the listeners, both children and adults, used the formant transition cue to determine their phonemic judgments.

Summary

It appears that dynamic information of initial phoneme plays an important part n identifying the place of stop consonants. Little attention has been given to comparing information provided by the static burst to that of the dynamic transition.

Normal-hearing Listeners: Children

Studies of children’s speech perception have shown that children perceive speech differently than do adults. In particular, the DWS hypothesis states that children are more focused on dynamic cues, especially, F2 transition cues, than steady-state cues for making phonemic decisions in fricative consonants (Nittrouer, 1992).

Based on a series of studies conducted by Stevens and Blumstein (1978) and Blumstein and Stevens (1979, 1980), the "global" spectrum property which is the initial short-term spectrum cue of stop consonant production is the most efficient cue in identifying the place of articulation of stop-consonants. The ability to use secondary cues, such as formant transition, is acquired by language experience. In terms of this theory, children use the gross shape of integrated burst and initial portion of formant transition for identification of place of articulation. During perceptual development, children learn how to use the separate burst and formant transition cues (Blumstein & Stevens, 1980).

Ohde, Haley, Vorperian, and McMahon (1995) investigated the different acoustic properties for the perception of place of articulation in stop consonants in terms of development perspective. One adult group and five groups of children (5, 6, 7, 9, and 11 years of age) participated. All combinations of /b, d, g/ and /i, a/ were manipulated for the following variables: formant transition (moving vs. straight), noise burst (present vs. absent), and voicing duration (10ms vs. 46ms). The parameters of stimuli were adapted from Blumstein and Stevens (1980). The results revealed that dynamic transition cues are not necessary to identify the place of articulation in all groups except [b] in the context of [i]. This finding contradicts those of Walley and Carrell (1983). Also, the burst cue was important for identification of [d] and [g], and the presence of burst cues was particularly salient for older children (11 years old) and adults, suggesting a pattern of development in the ability to integrate spectral cues. Also, 5-year-old children have the ability to identify stimuli as short as 10ms. Increasing duration of voicing gave more perceptual benefit to older children (11 years old) and adults.

Another development study of vowel perception in the presence of stop-consonants was assessed by Ohde, Haley, and McMahon (1996). Stop consonants [b, d, g] were used with the [i, a, u] vowel environment. The durations of stimuli were manipulated in moving transition or straight transition cues. The children were 5, 6, 7, 9, and 11 years of age, and a group of adults also participated. The findings of this study concluded that young children could perceive vowels with short duration stimuli except for [ga]. More specifically, some longer duration stimuli were better identified by young children, but duration did not significantly affect perception in adults, suggesting children depend on the final value of formant transition for vowel identification.

Ohde and Haley (1997) studied 3- and 4-year-old children with the same stimuli as in Ohde et al. (1996). The results supported the conclusion that the onset of stimuli was important to identify stop consonant stimuli in 3- and 4-year-old children. Also, developmental patterns of weighting formant transition were observed, but this was limited to the context of [g]. Generally, burst cue and formant transition cues improve identification of stop-consonant perception for the children and adults in this experiment.

Sussman (1993 a, b) suggested that younger children (4 years old) have less sensitivity in perceiving formant transitions in [ba–da] continuum compared to older children and adults. In Sussman’s (2001) study, 4-year-old children and adults primarily use longer and more intense cues, such as steady-state cues, for identifying a vowel in CV syllables. Taken together, children have less ability to use short duration cues, such as formant transition cues, due to immature auditory sensitivity. Thus, children in some cases use steady state cues rather than dynamic cues to make phonemic decision. These results contradict the DWS hypothesis.

On the other hand the findings of Hicks and Ohde (2005) support the DWS hypothesis. They studied the perception of stop-glide contrast [ba–wa] by 4- to 5-year-old children. The stimulus continua were manipulated in the following three conditions: (1) the F1 and F2 formant transition varied along with transition duration from 15ms (appropriate for [ba]) to 65ms (appropriate for [wa]), (2) a burst cue was added onto the /ba/ endpoint and the amplitude of the burst across the continuum to 0 for the /wa/ endpoint was gradually reduced, and (3) the F1, F2 and F3 formant transitions varied appropriate between /ba/ and /wa/ while higher formants remained the same as under the first condition. In each condition, three syllable durations (105ms, 170ms, and 315ms) were tested as contextual effects. The results showed all groups use transition duration cues as primary cues for perception of this continuum in all conditions; however, the burst cue did not significantly influence context effect in either group. In addition, in comparing the first and third conditions, the children's perception was more affected by formant transition frequency than those of the adults. In the third condition, the children also focused more on frequency of formant transition than duration of syllables. That is, children are biased toward formant transition. This is evidence in favor of the DWS hypothesis.

Summary

The DWS hypothesis (Nittrouer, 2002) stated that children showed a strong bias toward formant transition cues because they are dynamic cues; however, Sussman's (1993b, 2001) hypothesis suggested that children use longer duration or more intense cues due to immature auditory sensitivity, such as to steady-state cues. Some studies in stop consonants showed children and adults use transition cues equally well; however one recent study (Hicks and Ohde, 2005) showed that children use transition cues more than adults. Thus, the developmental findings for stop consonants are controversial.

Hearing-impaired Listeners: Adults

It is well known that listeners with SNHL have difficulty in identifying the place of stop consonant articulation. It has been suggested that these listeners possess less ability to perceive short formant transition cues used for identification of place of stop consonants (Owens, Benedict, & Schubert, 1972; Dorman, Marton, Hannley, & Lindholm, 1985). Another possible problem for identification by hearing-impaired listeners is the poor frequency resolution of hearing-impaired listeners (Lindholm, Dorman, Taylor, & Hannley, 1988).

According to the study by Dubno, Dirk, and Schaefer (1987), perception of place of short duration stop consonants depends on the configuration of hearing impairment with high frequency hearing loss. Hearing-impaired listeners with flat, gradual, or steeply sloping hearing losses were assessed. The stop consonants [b, d, g] were paired with [a, i, u] vowels. The duration of syllables were manipulated from 300ms to 10ms. Results showed that performance of identification in [a] and [u] vowel environments decreased as the slope of hearing loss configuration increased. That is, the audibility of stimulus is related to the ability to identify place of articulation of stop consonants. The significant improvement was demonstrated between 10ms and 30ms. However, performance of identification in [i] environment was poor for all hearing impaired groups regardless of hearing loss configuration and the duration of syllables. The authors explained that because transition cues were not significantly different across three stop consonants in [i] vowel environment, hearing impaired groups could not identify the place of articulation in even longer duration of syllables.

Van Tasell, Hagen, Koblas, and Penner (1982) suggested that auditory distortions such as impaired frequency resolution with loudness recruitment and absence of suppression may have little effect on the perception of speech by moderately hearing-impaired subjects. In addition, Turner, Souza and Forget (1995) claimed that poorer temporal acuity by listeners with hearing loss did not affect their speech perception. Dorman et al. (1985) suggested hearing-impaired listeners made errors in identifying the place of stop consonants because of a limited perception of dynamic information. Normal-hearing adults, both young (<40 years old) and elderly (>60 years old), and elderly, hearing-impaired adults (>60 years old) were evaluated for their ability to perceive places of stop consonants with manipulation of F2 onset frequencies, and the results indicated abnormal performance of identification in the hearing-impaired group.

If hearing-impaired listeners have problems with the short duration of F2 transition cues, they might be better able to identify longer duration of F2 transition cues. Ochs, Humes, Ohde, and Grantham (1989) manipulated the duration of F2 transition cues while preserving onset spectrum. Results showed that both listeners with normal hearing and listeners with hearing loss improved identification with longer duration of the F2 transition cues. However, Turner, Smith, Aldridge, and Stewart (1996) investigated hearing-impaired listeners with durations of F2 onset as long as 80 or 160 ms, but the subjects did not achieve the identification performance levels of listeners with normal hearing. Lindholm, Dorman, Taylor, and Hannley (1988) investigated the effects of formant transitions, spectral shapes (tilt), and abruptness of frequency change in normal-hearing and hearing-impaired listeners. The stimuli with conflicting transition cues and shapes were manipulated by adjusting the formant amplitudes to that of the prototype stimulus having the proper tilt. The results revealed that identification abilities varied depending on hearing status. That is, spectral tilt and abruptness of frequency change affected the hearing-impaired listeners' responses, while formant transitions were important for the normal-hearing listeners. The authors assumed that formant transitions were the primary cue. The authors of the study proposed that abnormality of frequency resolution and temporal resolution affected the identification of stimuli and might lead to distortion of the primary cue, in which case the secondary cue may be used to identity phonetic categorization.

Specific acoustic information, such as burst amplitude, onset spectra, and transition cue, affects the perception of consonantal place. One of these cues is the relative amplitude spectral cue. Relative amplitude is defined as the spectral peak of consonant in the F4/F5 frequency region relative to the vowel onset amplitude at F4. For example, higher consonant burst amplitude than vowel amplitude in the F4/F5 frequency results in more alveolar than labial stop consonant responses (Hedrick, Schulte, & Jesteadt, 1995). Hedrick et al. (1995) studied the effect of relative amplitude and transition cues in relation to presentation levels in hearing-impaired listeners. Results revealed that hearing-impaired listeners give more weight to relative amplitude cues than to transition cues in the voiceless stop consonant contrast (/p/—/t/). Also, hearing-impaired listeners chose more alveolar responses compared to normal-hearing listeners at the same presentation level. In a study conducted by Hedrick and Jesteadt (1996), only amplitude cues were manipulated in /p/—/t/ contrasts to investigate any differences in perceiving the relative amplitude change between normal-hearing listeners and hearing-impaired listeners. The results showed that there were no significant differences between the two groups. The authors suggested that abnormal growth of responses was not the reason for more alveolar responses from listeners with hearing loss. Instead, the hearing-impaired listeners had a different weighting strategy for the cues for place of articulation than did the listeners with normal hearing. Taking the two studies together, it can be seen that hearing-impaired listeners use the transition cue differently than normal-hearing listeners.

The Frequency-Following Responses (FFR) of hearing-impaired listeners were assessed for the formant transition cues of stop consonants (Plyler &Ananthanarayan, 2001). The results demonstrated that FFR was not recorded in hearing-impaired groups, suggesting degradation in the neural representation of the second formant transition. The authors speculated that the degradation of neural representation might cause a reduction of identification perceptual performance.

The cue weighting strategies of hearing-impaired listeners, especially in cochlear implant users, were not significantly related to speech recognition accuracy (Iverson, 2003). In this study, manipulated Voice Onset Times (VOTs) of the /d/—/t/ continuum were used to investigate identification boundaries and two speech recognition tasks were performed in cochlear implant users and normal-hearing listeners. The results showed that the VOTs of identification boundaries were significantly longer than those of normal-hearing listeners, but word recognition scores were not significantly related to the individual VOT identification boundaries. That is, if the cochlear implant user does not have similar VOT boundaries, speech (words) could still be accurately perceived.

Summary

Hearing-impaired listeners have less ability to perceive short formant transition cues used for identification of place of stop consonants due to short duration. The perceptual weighting strategies of hearing-impaired listeners were significantly different than those of normal-hearing listeners, perhaps because hearing-impaired listeners have less audibility, poorer frequency and temporal resolution, and degradation of neural representation. However, the cue weighting strategies of hearing-impaired listeners, especially CI users, were not related to their speech recognition ability.

Hearing-impaired Listeners: Children

The developmental perceptual strategies of children with hearing loss are still not clear (Pittman, Stelmachowicz, Lewis, & Hoover, 2002). In general, children with SNHL had relatively fewer problems in perceiving the voicing features than in identifying the place feature of the consonant syllables (Byers, 1973; Erber, 1972).

Parady, Dorman, and Whaley (1981) assessed the identification and discrimination of a stop consonant voicing contrast /da/—/ta/ continuum in hearing-impaired children and adolescents with moderate, severe, and profound SNHL. The VOTs ranged from -10ms to 60ms in 10m steps, and between 20ms and 40ms in 5m steps. The results indicated that prolonged phoneme boundaries occurred in the profound hearing loss group. Also, phonemic functions of the hearing-impaired functional graph were shallower than those of normal-hearing listeners, suggesting that more stimuli were ambiguous for the hearing-impaired group. In addition, there was no relationship between duration of amplification use and identification of VOT.

Similarly, Johnson, Whaley, and Dorman (1984) investigated three pairs of stop voice and voiceless consonant phonemic boundaries (/ba/—/pa/, /da/—/ta/, and /ga/—/ka/) depending on VOTs in normal-hearing and hearing-impaired children. Two, six, and four alternative condition tests were used for validity. There were no significantly different phonemic boundaries among the normal, mild, and moderate hearing loss groups. However, the profound hearing loss group had a longer phonemic boundary than those of the other groups and also exhibited slight differences within the boundaries along with place of articulation. The results suggested cochlear damage does not affect the perception of VOT in listeners with mild to moderate hearing loss, but profound hearing loss does affect the processing of VOT.

Summary

Hearing-impaired children have significantly different phonemic boundaries than those of normal-hearing children in VOT. The VOT of hearing-impaired children, especially those with profound hearing loss, is longer than that of normal-hearing listeners, due to damaged cochlea. Identification of VOT was not related to duration of amplification use.

RATIONALE FOR RESEARCH

Although many studies investigating developmental speech perception cue weighting strategies have been conducted, it is still unclear why and how speech cue weighting strategies differ between children and adults. Also, few studies have been conducted regarding the perceptual development of hearing-impaired children, especially cochlear implant users. Knowledge of perceptual weighting in children with normal hearing, as well as children with hearing impairment, will provide insight about the auditory mechanism of speech processing and information regarding the effect of signal processing on perceptual development and speech/language intervention.

In order to investigate the perceptual weighting strategies in children with normal hearing and those wearing cochlear implants, steady state cues were fixed at appropriate frequencies for fricative consonant ([s]—[ʃ]) contrast and for ([p]—[t]) stimuli contrast voiceless stop consonant contrast in [u] vowel environment. Also, transition cues were manipulated appropriately for end points of each continuum, and neutral transition cues were made for fricative consonant and voiceless stop consonant continua. In fricative consonants, fricative noise cues (static cues) are longer than transition cues (dynamic cues). Conversely, in voiceless stop consonants, transition cues are relatively longer, and burst cues (static cues) are shorter than those of fricative consonants. Thus, it is possible to observe how two cues—steady-state and transition — are weighted differently due to changes in duration.

Previous studies used the differences in phonemic boundaries (i.e. the 50% identification points) and slopes of psychometric functions between groups for analysis (Nittrouer, 1996, 2002). Also, one study (Nittrouer, 2002) applied regression analyses to determine partial correlation coefficients. However, these analyses could not provide the percent of variance accounted for by each cue. Moreover, interaction or integration cues could not be considered. However, the ANOVA model (Hedrick & Younger, 2001, 2003, 2007) can provide relative proportions as well as a crude interaction, or integration, of the cues. In this model, the weights were referred to as coefficients of determination, which is to say, eta-squares. These weights were obtained by running an ANOVA for each group using the cues as factors. The weights were obtained by dividing the sum of squares for a given factor by the total sum of squares. The weights determined the percentage of variance accounted for by each cue and by cue interaction making it possible to observe the speech cue weighting strategies of each group.

For fricative consonant continua, given the DWS hypothesis (e.g., Nittrouer, 1992), it is hypothesized that children focus more on F2 transition cue and less on fricative spectrum cue than adults. This follows the DWS assumption that children place relatively more weight on a dynamic cue rather than a steady-state cue. However, the DWS hypothesis does not suggest which cue will have the most absolute weight within a group. Given auditory sensitivity hypothesis (Sussman, 1993b, 2001), children may place more weight on the fricative spectrum cue than transition cue, because the duration of the fricative spectrum cue is longer than that of the transition cue. In addition, children wearing cochlear implants may use the fricative spectrum and transition cues less than normal hearing children, because 1) fricative noise has relatively high frequency energy and 2) the transition cues are of short duration.

For the voiceless stop consonant continua, the transition cue is relatively longer than that of the burst cue. In terms of DWS and auditory sensitivity hypothesis, children and adults may give more attention to the transition cue, since the transition cue is longer cue (auditory sensitive hypothesis) and a dynamic cue (DWS hypothesis). Also, it may be possible that all groups place more weight on the integration cue of cues in stop consonant syllables than fricative consonant syllables. Compared between groups, children may weight more the transition cue than adults in terms of DWS hypothesis. Moreover, children wearing cochlear implants may have more difficulties to perceive the stops, because the stimuli are shorter than fricative noise sounds. Thus, the primary goal of this study is to determine the speech weighting strategies for fricative consonant syllable and voiceless stop consonant syllables in children with normal hearing and children wearing cochlear implants using ANOVA model (Hedrick and Younger, 2001, 2003, 2007). Specifically, the following goals were addressed:

1. To examine developmental changes of cue weightings on fricative noise consonant syllables and stop consonant syllables between normal hearing adults and normal hearing children;
2. To examine differences in cue weighting between normal hearing children and children wearing cochlear implants;
3. To examine the two main developmental speech cue hypotheses–DWS (Developmental Weighting Shift) hypothesis (e.g., Nittrouer, 1992) vs. Auditory sensitivity hypothesis (Sussman, 1993b, 2001).

CHAPTER III

METHODS

Subjects

Three groups participated in this study: ten adults with normal hearing (NHA) (Female = 5), eleven children with normal hearing (NHC) (Female = 5), and eight children wearing cochlear implants (CI) (Female = 8). The mean age of the NHA group was 24.5 years old (s.d. 2.0 years, range 22~27), the NHC was 6.5 years old (s.d. 1.2 years, range 5.5~8.4), and the CI was 7.5 years (s.d. 1.0 years, range 6.0~8.9). All participants were native speakers of American English. All listeners with normal hearing had hearing sensitivity in both ears of 20 dB HL or better for octave frequencies from 250 to 4000 Hz (ANSI S3.6-1996) and no history of otologic pathology. Children wearing cochlear implants had hearing sensitivity with cochlear implants of 40 dB or better for octave frequencies from 250 to 4000 Hz and no history of cognitive problems. Figure 1 indicates the auditory thresholds obtained the implants in the soundfield. One child with cochlear implants wore bilateral cochlear implants (CI 7). Table 1 shows further data regarding the children wearing cochlear implants and core language scores (CELF-4®, Clinical Evaluation of Language Fundamentals-4®, Semel, Wiig, & Secord, 2003) for the children wearing cochlear implants. Core language scores include expressive and receptive language scores. All children with normal hearing also had CELF-4® screening tests and showed normal language development. One child in the normal hearing group refused to have the language test (NHC11). The individual core language standard scores are shown in Table 2.

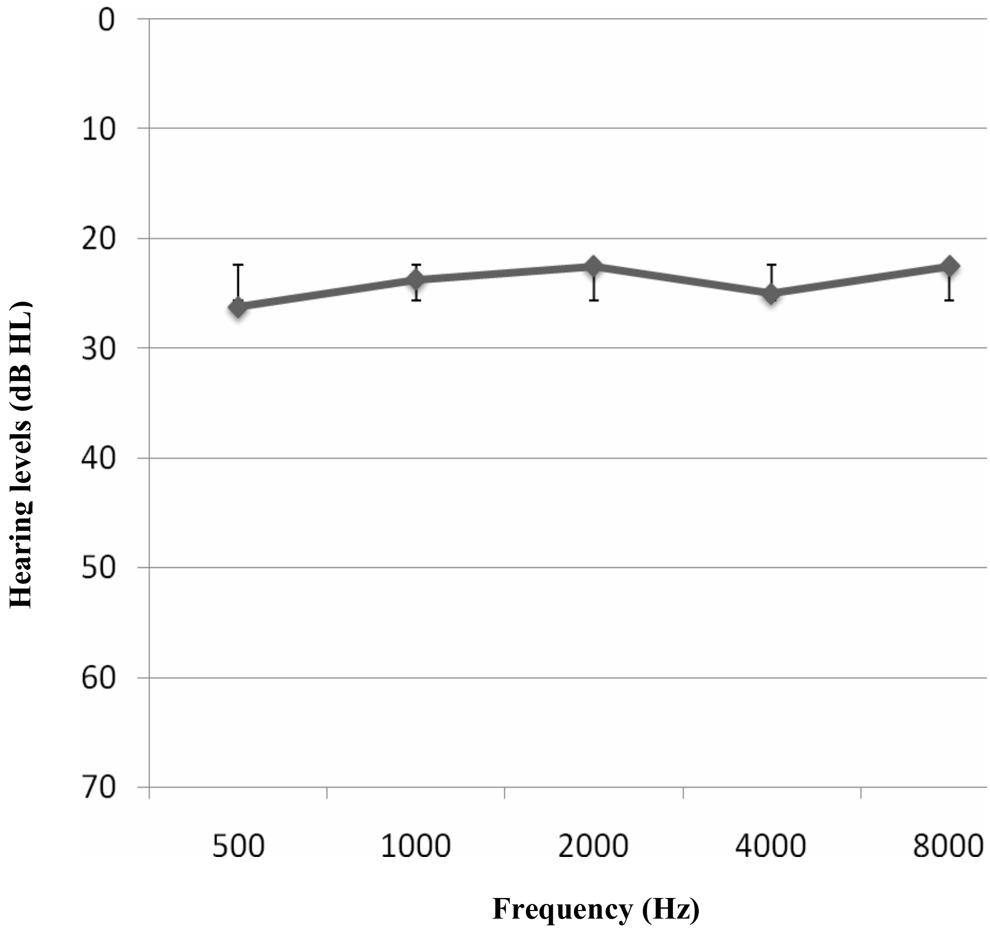

Figure 1: Audiometric thresholds with cochlear implants for children wearing cochlear implants. Error bar mean 1 SD (Standard Deviation).

Table 1: Description of Children Wearing Cochlear Implants

	Age	Onset Age of identification (yrs)	Etiology	Onset age of amplification (yrs)	Age of implantation (yrs)	Frequency of speech and language therapy (hrs)	CI internal device	Speech processing strategy	CELF-4® Core language score (Standard Score)
CI1	6.9	1.9	Unknown	2.3	2.7	6	CI24R	ACE	40
CI2	7.4	3.0	Unknown	3.5	3.5	6	Hi90K	ACE	40
CI3	8.9	3.5	Unknown	3.5	6.0	2	CI24R	ACE	45
CI4	8.9	3.5	Unknown	3.5	6.0	2	CI24R	ACE	45
CI5	6.9	0.2	Prematurity	0.5	2.0	2	CI24R	ACE	33
CI6	7.9	1.2	CMV	1.3	2.0	1	CI24R	ACE	46
CI7	6.0	0.5	Unknown	1.3	0.7	1	CI24R/ Combi40+	ACE	82
CI8	7.4	2.0	Gene mutation	2.5	3.0	4.5	CI24R	ACE	67
Average	7.5			2.0	3.2	3.0			50

Table 2: Individual Core Language Standard Scores for Children with Normal Hearing (NHC)

	Age (yrs)	CELF-4® Core language score (Standard Score)
NHC1	6.1	99
NHC2	5.5	109
NHC3	8.4	112
NHC4	5.0	112
NHC5	7.1	123
NHC6	6.1	91
NHC7	7.9	124
NHC8	6.0	118
NHC9	8.0	108
NHC10	5.5	121
NHC11	5.0	-
Average	6.6	111.7

All normal-hearing adult listeners were recruited from undergraduate and graduate students of the Department of Audiology and Speech pathology at the University of Tennessee. All normal-hearing children were recruited from the children of faculties and students of the Department of Audiology and Speech pathology, and children wearing cochlear implants were recruited from the Child Hearing Service (CHS) and the Audiology Clinic at the University of Tennessee. Hearing loss etiological data were obtained from medical charts or the case history forms.

Stimuli

Synthetic consonant-vowel (CV) stimuli were constructed via a software cascade/parallel formant synthesizer (Klatt, 1980). The sampling rate for stimulus generation was 10 kHz. Continua corresponding to consonant contrast were constructed: /su/ — /ʃu/ and /pu/ — /tu/. For each stimulus contrast, combinations of ideal frication/burst and formant transition onset frequency were used to create 9 stimuli. Synthetic CV continua representing /su/ — /ʃu/ and /pu/ — /tu/ syllables were constructed using a software cascade/parallel formant synthesizer (Klatt, 1980) at a sampling rate of 10 kHz.

Experiment I: Fricative Consonant Perception

For the frication consonant contrast, the /su/ — /ʃu/ stimuli were made. First, a /s/ spectrum was constructed, with energy in the F4 frequency region (3700 Hz). Energy in this frequency region was shown in a previous study to convey a /s/ percept (Hedrick, Bahng, & von Hapsburg, submitted). This fricative was then combined with F2 formant transition onset frequencies appropriate for /s/ (F2 onset = 1200 Hz), /ʃ/ (F2 onset = 1800 Hz), or neutral (F2 onset = 1500 Hz). This made three stimuli. A /ʃ/ spectrum was then made with energy in the F3 frequency region (2200 Hz). This frication was combined with the three formant transition values to yield three more stimuli.

Finally, a frication spectrum neutral for the /s/ —/ʃ/ contrast was created, with an energy peak at 2950 Hz. This neutral spectrum was combined with the formant transition values to yield the final three stimuli. The stimuli varied in terms of the frequency of the fricative spectrum and vowel onset of transition (F2 transition).

The current study used the three poles of noise frequency spectrum were. The pole frequency of 2200Hz is most /ʃ/ like, 2950 Hz is between /ʃ/ and /s/, and 3700 Hz is most /s/ like. For the formant transition cues, the F2 onset frequency was 1200 Hz, 1500 Hz, or 1800 Hz. The F2 onset of 1200 Hz is most /s/ like, and the F2 onset of 1800 Hz is most /ʃ/ like (Table 3). Figure 2 shows the stylized spectrogram of each syllable for fricative consonant continuum. Particular effort was made to equate fricative amplitude for pairs of stimuli having the same fricative pole but different formant transition.

Table A1— A3 of Appendix A presents the synthetic parameter used to create the representative stimuli.

Experiment II: Voiceless Stop Consonant Perception

The stimuli /pu/—/tu/ were used for the stop consonant contrast. A /pu/ burst was created having a relatively flat spectrum. This /p/ burst was then combined with F2 formant transition onset frequencies corresponding to either /p/ (F2 onset = 800 Hz), /t/ (F2 onset = 1600 Hz), or neutral (F2 onset = 1300 Hz). This yielded three stimuli. Then, a /t/ burst was created by increasing the energy in the F4/F5 frequency region, and this burst was then combined with the three F2 formant transition onset frequencies to yield three more stimuli. Finally, a neutral burst was created by inserting energy values in the

Table 3 Description of Stimuli of Experiment I

Spectrum / Transition	Most /ʃ/ like (2200Hz)	Neutral (2950Hz)	Most /s/ like (3700Hz)
Most /su/ like (1200Hz)	ʃFST	NFST	**SFST (Most /su/ like sound)**
Neutral (1500Hz)	ʃFNT	NFNT	SFNT
Most /ʃu/ like (1800Hz)	**ʃFʃT (Most /ʃu/ like sound)**	NFʃT	SFʃT

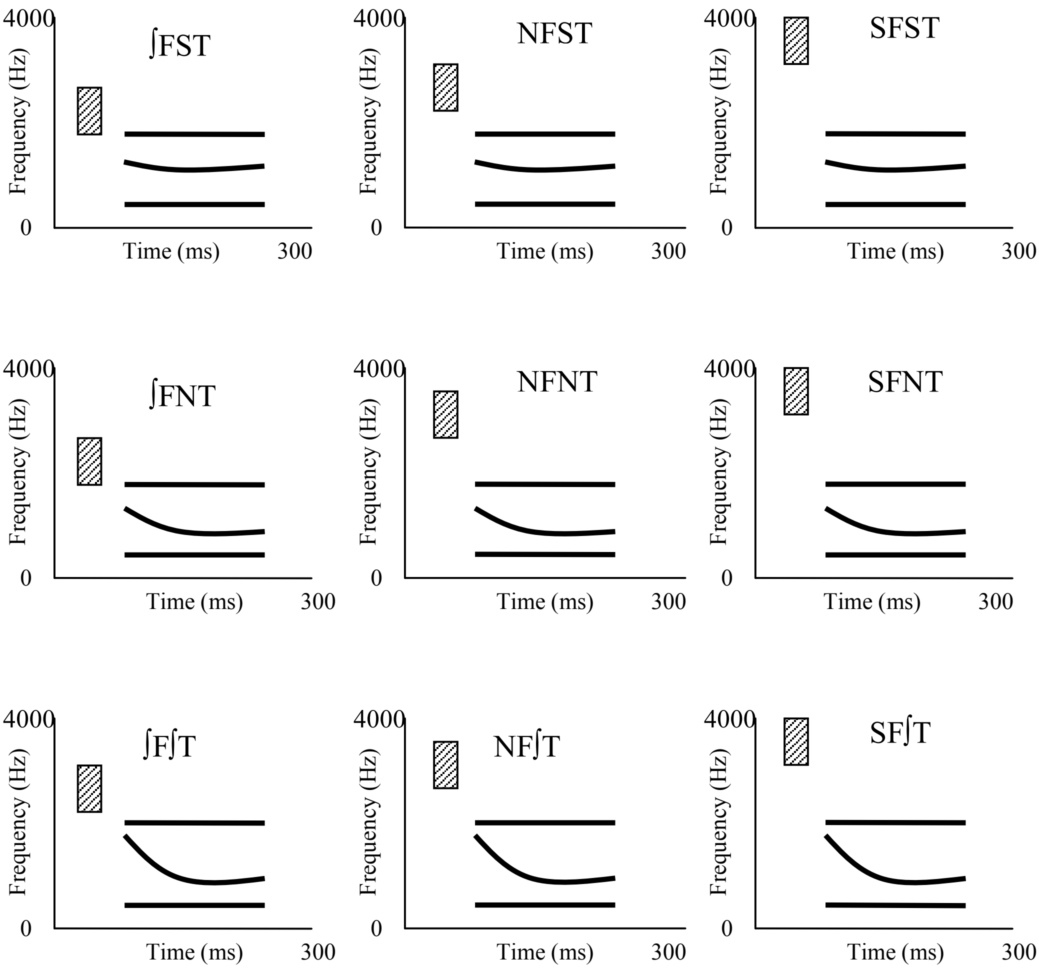

Figure 2: Stylized spectrograms of each syllable for fricative noise consonant continua. Fricative spectrum cues are highlighted with diagonal lines. Vowel-onset formants are presented with solid lines. S - most /s/ like; N- neutral; ʃ - most /ʃ/ like. F - fricative spectrum, T - transition. For example, SFST stimulus has most /s/ like fricative spectrum cue with most /su/ like F2 onset transition cue.

F4/F5 frequency region (3300-4200 Hz) that were intermediate of the /p/ and /t/ burst cues.

This neutral burst was then combined with the three F2 formant transition onset frequencies to yield 3 more stimuli (Table 4). Figure 3 showed stylized spectrograms of each stimulus for voiceless stop continuum. Thus, the /pu/ - /tu/ contrast consisted of 9 stimuli. Tables B1— B3 of Appendix B present the synthetic parameters used to create the representative stimuli.

Recording System

All stimuli were digitally synthesized and controlled by a signal generation system (Tucker-Davis, System II) interfaced to a microcomputer (Compaq 2000, 166 MHZ). Digital signal generation, including control of parameters, was accomplished by interactive signal generation and control software (CSRE Version 4.5). Stimuli were routed from the computer (Dell, Latitude D810) with a controlled psychological experimental software program (Super lab pro, Version 2.0.4), then to a loudspeaker (JBL, proIII) located in a double-wall sound-treated booth (IAC, #105884). Sound levels were expressed as the sound pressure level measured in a one-inch condenser microphone coupled to a sound level meter (Larson Davis, CA250, #2893).

Participants were seated in the double-wall sound-treated booth and were given instructions. Following each stimulus presentation, participants responded by pressing an appropriate picture on the keypad. Participants who could not use the keypad were asked to point to the screen as a response (shown on the computer screen). If the participant was a child, she/he got reinforcement. Stimuli were presented to the listeners at 70 dB SPL via a loudspeaker. Participants were seated at a distance of 1m from a loudspeaker.

Table 4 Description of Stimuli for Experiment II

Transition \ Burst	Most /t/ like (Strong amplitude in F4/5)	Neutral (Moderate amplitude in F4/5)	Most /p/ like (Soft amplitude in F4/5)
Most /pu/ like (800Hz)	TBPT	NBPT	**PBPT (Most /pu/ like sound)**
Neutral (1300Hz)	TBNT	NBNT	PBNT
Most /tu/ like (1600Hz)	**TBTT (Most /tu/ like sound)**	NBTT	PBTT

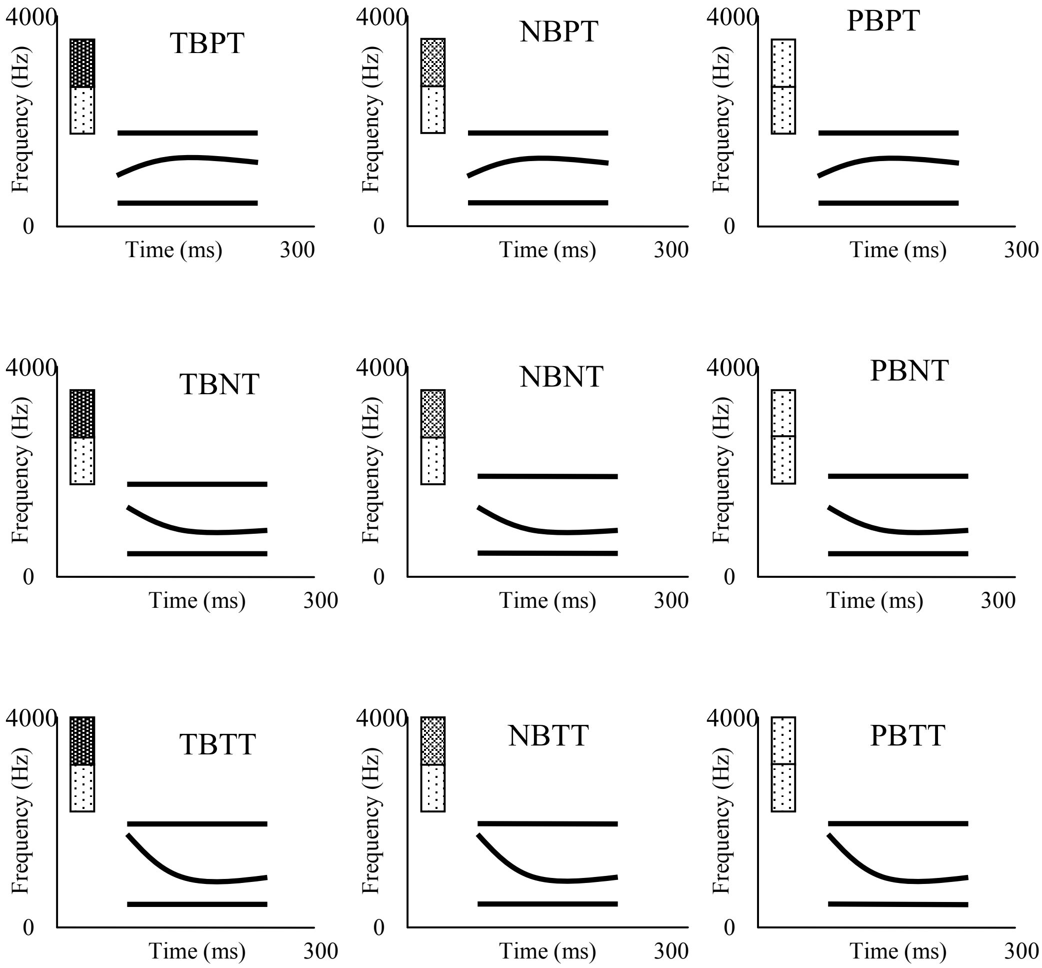

Figure 3: Stylized spectrograms of each syllable for voiceless stop consonant continua. Burst amplitude cues are highlighted with diagonal lines. Vowel-onset formants are presented with solid lines. P - most /p/ like; N- neutral; T - most /t/ like. B – Burst amplitude, T - transition. For example, PBPT stimulus has most /p/ like Burst cue with most /pu/ like F2 onset transition cue.

This is a moderately loud listening level; the signals posed no threat to hearing.

Response Evaluation

Participants' responses were automatically saved to the Microsoft Excel program from Super lab pro (version 2.0.4). Psychometric functions displaying the percentage identification as /s/ responses for Experimental I and /p/ responses for Experimental II were generated for each continuum for each subject and each group.

Experiment Protocol

Participants and parents or guardians of participants first read and signed the informed consent form containing all pertinent information regarding the experiments and participation in them (Appendices C & D). They were also asked to complete an audiological history (Appendices E & F). For normal-hearing listeners, pure-tone air-conduction thresholds, tympanometry, and otoscopy were performed at the beginning of the experimental session. For children wearing cochlear implants, aided soundfield thresholds were obtained instead of air-conduction thresholds. The information about their residual hearing thresholds was obtained from their clinic or medical charts.

Experiment I: Fricative Consonant Perception

Practice items were presented to all listeners before tests. A picture of a shoe served as the prompt for the stimulus /ʃ /, and a picture of a girl served as the prompt for the /s/ stimulus. First, the investigator asked about /su/ and /ʃu/ with live voice. Then participants listened to the end point sounds of continua (most /su/ like and most /ʃu/ like sounds) via loudspeaker (JBL, proIII). Practice items were administered 5 times for each sound for a total of 10 times. If the participant did not get all 5 correct of each sound, the data were not included. Participants listened to a total of 14 stimuli presented 10 times each, for a total of 140 responses. The stimuli were presented in random order. Children listened to 70 stimuli and had a break; after the break, they listened to other 70 stimuli. Adult listeners did not have a break during the test.

Experiment II: Stop Consonant Perception

The procedure for Experiment II was the exactly same as for Experiment I except the pictures shown on the computer screen. A picture of "Winnie the Pooh" served as the prompt for the stimulus /p/, and a picture of "2" served as the prompt for the /t/ stimulus. The rest of procedures were same as in Experiment I.

CHAPTER IV

RESULTS

Experiment I: Fricative Consonant Perception

Normal- Hearing Adults (NHA) and Children (NHC)

The mean labeling responses from normal hearing adults (NHA) are presented in Figure 4, and the mean labeling responses from normal hearing children (NHC) in Figure 5. Each figure indicates the average responses of /s/ responses as a function of pole frequency spectrum, and the figure legend designates type of formant transition (/su/-like, neutral, and /ʃu/-like). Specifically, filled diamonds represent responses from stimuli with a F2 transition onset frequency value appropriate for /ʃu/ (e.g., 1800 Hz), solid squares represent responses from stimuli with a F2 transition onset frequency value appropriate for neutral (e.g., 1500 Hz), and solid triangles represent responses from stimuli with a F2 transition onset frequency value appropriate for /su/ (e.g., 1200 Hz). In Figures 4 and 5, there are clearly defined categories for both best exemplar fricative sounds (e.g. /s/ pole frequency with /su/ F2 transition stimulus and /ʃ/ frication spectrum with /ʃu/ F2 transition stimulus). In comparing Figures 4 and 5, the labeling functions from the NHA were steeper and showed more separation than those of the NHC, suggesting more weight placed upon the fricative spectrum pole frequency.

The following analyses were performed on the data: (1) a three-way analysis of variance (ANOVA) to determine group differences, and (2) a determination of relative cue weights within groups using the ANOVA model (Hedrick & Younger, 2001, 2003, 2007). The responses were arcsine-transformed, and then entered as the dependent

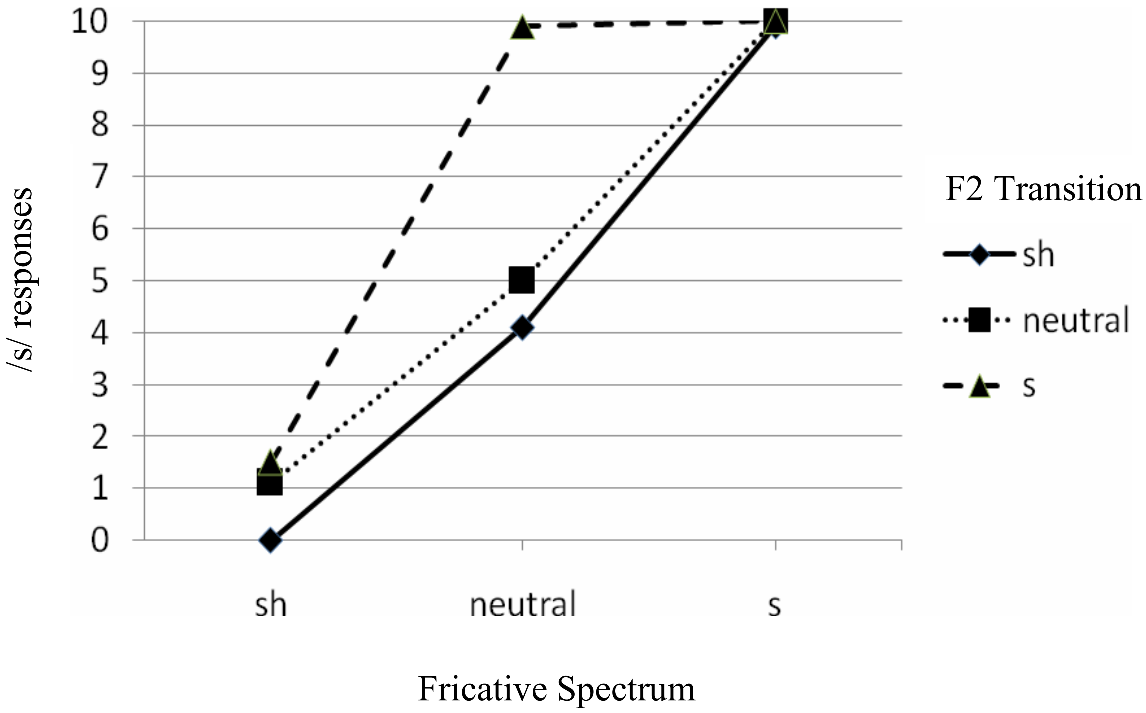

Figure 4: Mean /s/ responses from the NHA group plotted as a function of fricative spectrum. The legend indicates that diamonds represent responses from stimuli with a F2 transition onset frequency value for /ʃ/, squares represent responses from stimuli with a neutral F2 transition onset frequency value, and triangles represent responses from stimuli with a F2 transition onset frequency value for /s/.

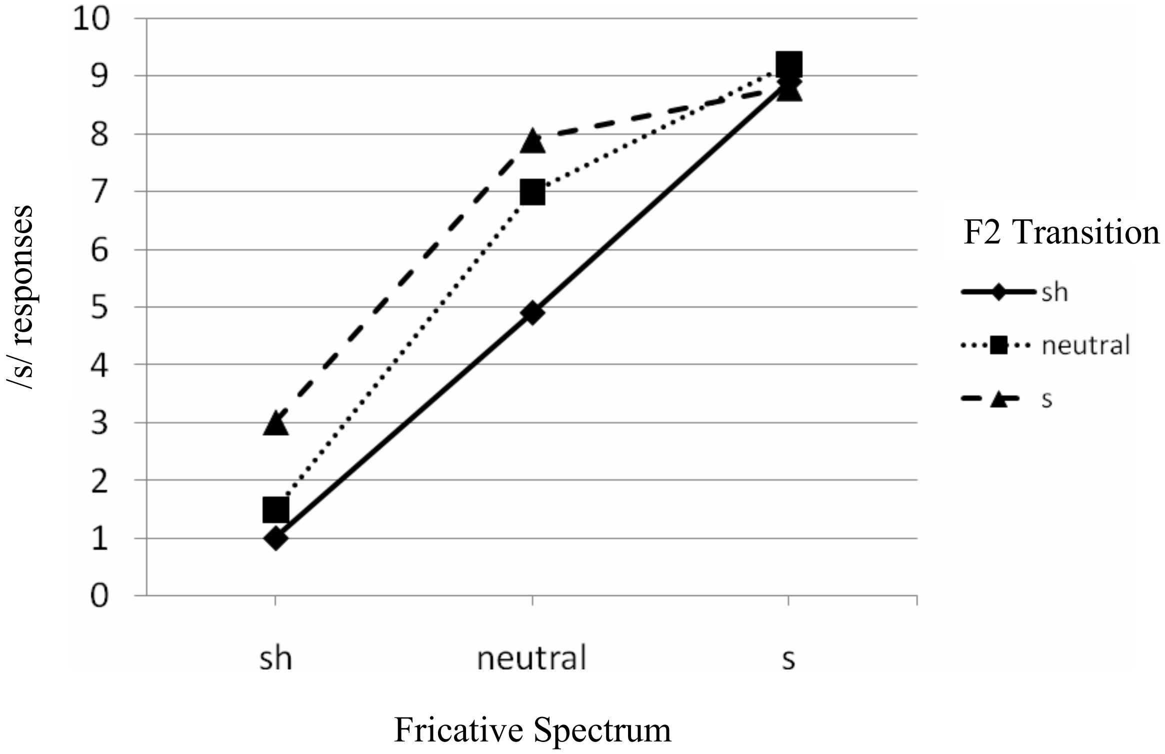

Figure 5: Mean /s/ responses from the NHC group plotted as a function of fricative spectrum. The legend indicates that diamonds represent responses from stimuli with a F2 transition onset frequency value for /ʃ/, squares represent responses from stimuli with a neutral F2 transition onset frequency value, and triangles represent responses from stimuli with a F2 transition onset frequency value for /s/.

variables in the three-way ANOVA. The within factors for this analysis were the two cues (frication spectrum and transition) and the between factor was listener group. The summary of this analysis is presented in Table 5. Each cue shows a significant main effect and there are significant two two-way interactions of frication spectrum by group and frication spectrum cue by transition cue. There was no significant interaction of transition by group. To explore the two-way interaction, one-way ANOVAs were performed for each CV stimulus to distinguish any differences between two groups. The summary of this analysis is presented in Table 6. A Holm's Bonferroni procedure was used to control for Type I error associated with multiple testing. A familywise error rate of .05 was adopted. These findings show that three out of nine stimuli resulted in significant differences between the NHA and NHC groups. This suggested that NHC and NHA groups have different perception strategies for fricative spectrum cues, not transition cues on these three stimuli.

To further analyze these results quantitatively, the relative perceptual weights given to the transition and spectrum cues, and their interaction, were calculated using the ANOVA model (Hedrick and Younger, 2001, 2003, 2007). These weights are presented in Table 7 and listed as the proportion of variance accounted for by the cue. For both children and adults the greater degree of weighting is on the frication spectrum cues than transition cues. Results showed that frication spectrum cues accounted for 84% of the variance in NHA responses, and 75% for NHC responses, suggesting there was a developmental pattern in fricative spectrum cue perception between adults and children groups. Transition cues and integration were similarly weighted. The proportion of weight placed on the transition cues and integration of cues was relatively minor in

Table 5: Results from the Three-way ANOVA Using Huynh-Feldt Corrections for NHA and NHC Groups in Fricative Noise Perception. The two within subjects factors were formant transition (Trans) and frication spectrum (Spect) cues and the between-subject factor was listener group (Group).

Factor	Degree of Freedom	F-ratio	Significant P-value
Trans	2.000	24.431	.000*
Trans X Group	2.000	.556	.578
Spect	1.676	299.385	.000*
Spect X Group	1.676	17.723	.000*
Trans X Spect	4.000	8.273	.000*
Trans X Spect X Group	4.000	1.108	.359
Group	1.000	9.482	.006*

* $p<.05$

Table 6: Summary of One-way ANOVAs at Each CV Stimulus for NHA and NHC Groups

Transition	Frication Pole	F-ratio	P-value	Adjusted P-value
/s/	s-like	11.179	.003	.023*
	Neutral	4.149	.056	.112
	ʃ-like	6.429	.020	.100
Neutral	s-like	2.380	.139	.139
	Neutral	7.745	.012	.071
	ʃ-like	17.024	.001	.004*
/ʃ/	s-like	4.716	.043	.128
	Neutral	20.031	.000	.002*
	ʃ-like	6.122	.023	.092

*p < .05

Table 7: Proportion of Variance Accounted for by Frication Spectrum and Formant Transition Cues, and the Interaction or Integration of the Cues.

Cues	NHA	NHC	CI
Spectrum	84*	75*	39*
Transition	3*	4*	11*
Integration	3*	3*	.3
Total	90	82	50.3

* means significant variance accounted for (p<.05)

comparison to the spectrum cue weighting. The total variance accounted for was greater for the NHA responses than for the NHC responses (90% vs. 82%), suggesting NHA response variation was more completely explained by the acoustic cue manipulations than for NHC group.

Normal-Hearing Children (NHC) and Children Wearing Cochlear Implants (CI)

The same analyses were performed on the data of normal hearing children (NHC) and children wearing cochlear implants (CI). The mean labeling responses from children wearing cochlear implants are presented in Figure 6. In comparing Figures 5 and 6, the labeling functions from the CI group were flatter than those of the NHC, suggesting less weight placed upon the fricative spectrum cues in CI group than in NHC group.

In order to determine the weighting of each cue, the three-way ANOVA was calculated. The within factors for this analysis were the two cues and the between factor was the listener groups. The summary of this analysis is presented in Table 8. It should be noted that each cue shows a significant main effect and there was a significant two-way interaction of frication spectrum by group. To explore the two-way interaction, a one-way ANOVA was performed for each CV stimulus to distinguish any differences between two groups. The summary of this analysis is presented in Table 9. The results reveal that three out of nine stimuli were significantly different between the NHC and CI groups. Results also indicate that there were no significant differences in best exemplars (SFST and ʃFʃT stimuli) between the two groups, suggesting that the CI group had a level of labeling ability for two best exemplars comparable to that of the NHC group. In the three-way ANOVA results, there were no significant differences in transition cues between the two groups. In addition, the one-way ANOVA results suggest that differences between

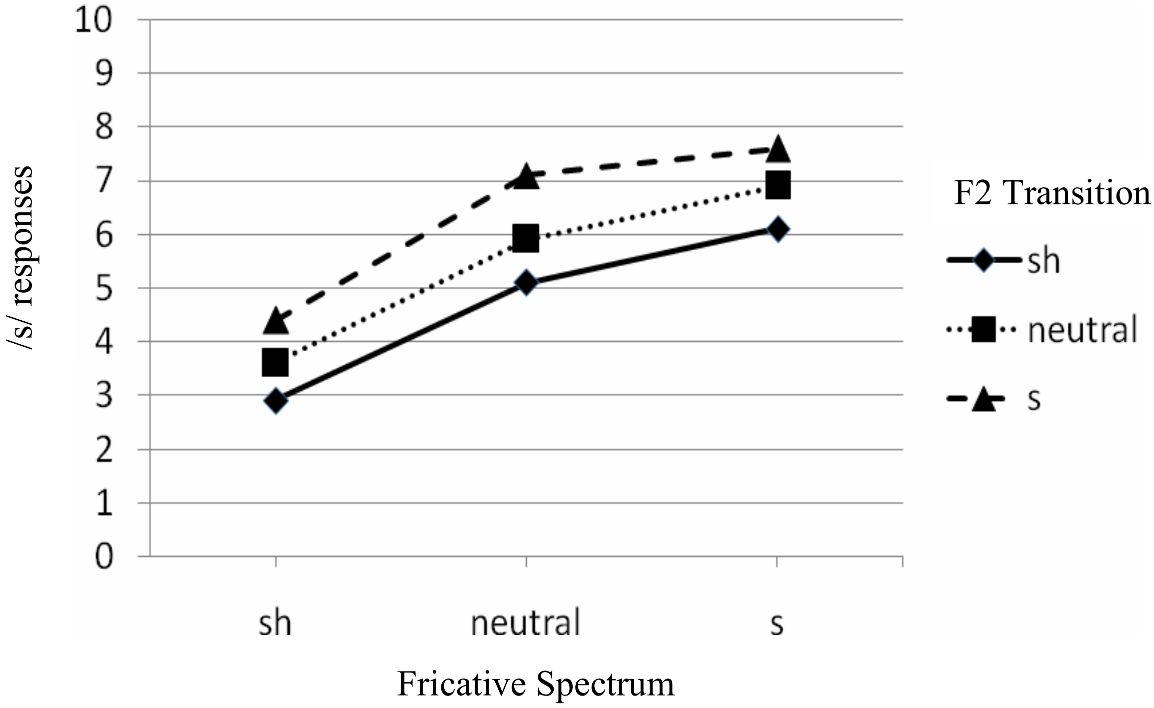

Figure 6: Mean /s/ responses from the CI group plotted as a function of fricative spectrum. The legend indicates that diamonds represent responses from stimuli with a F2 transition onset frequency value for /ʃ/, squares represent responses from stimuli with a neutral F2 transition onset frequency value, and triangles represent responses from stimuli with a F2 transition onset frequency value for /s/.

Table 8: Results from the Three-way ANOVA Using Huynh-Feldt Corrections for NHC and CI Groups in Fricative Noise Perception

Factor	Degree of Freedom	F-ratio	Significant P-value
Trans	2.000	22.505	.000*
Trans X Group	2.000	.330	.721
Spect	1.677	79.018	.000*
Spect X Group	1.677	13.531	.000*
Trans X Spect	4.000	1.697	.161
Trans X Spect X Group	4.000	1.471	.221
Group	1.000	.872	.363

*p <0.5
The two within subjects factors were formant transition (Trans) and frication spectrum (Spect) cues and the between-subject factor was listener group (Group).

Table 9: Summary of One-way ANOVA at Each CV Stimulus for NHC and CI Groups

Transition	Frication Pole	F-ratio	P-value	Adjusted P-value
/s/	s-like	2.896	.107	.535
	Neutral	16.242	.001	.008*
	ʃ-like	14.155	.002	.012*
Neutral	s-like	.798	.384	.768
	Neutral	2.223	.154	.463
	ʃ-like	.057	.813	.813
/ʃ/	s-like	2.384	.141	.564
	Neutral	10.531	.005	.033*
	ʃ-like	4.957	.040	.239

* p<.05

the two groups were found in SFNT, SFʃT, and ʃFNT stimuli. Taken together, different fricative spectrum cue weighting in CI group made a significantly different speech cue weighting strategy from NHC group.

The proportion of variance accounted for by each cue for each group is illustrated in Table 7. The fricative spectrum cue accounted for 75% of the variance of the NHC group responses but only 39% for the CI group responses. Transition cues accounted for 4% for NHC group responses and 11% for CI group responses. However, the latter was not a significant difference because there was no two-way interaction of transition cue by group in the three-way ANOVA results between the two groups. The total proportion of variance accounted for all cues was 82% for the NHC group and 50.3% for the CI group. Also, integration of cues was not significant in the CI group. These results imply that the CI group had less variance explained by the acoustic cue manipulation.

Summary of Results in Experiment I

1. There was significant difference in fricative spectrum cue weighting, whereas there was no significant difference in transition cue weighting among the three groups.
2. There was a developmental pattern for fricative spectrum cue weighting (NHA>NHC>CI).
3. The NHC and CI groups had similar labeling ability for best exemplars, suggesting different cue weighting strategies were not caused by a difference in labeling ability between two groups.

Experiment II: Voiceless Stop Consonant Perception

Normal-Hearing Adults (NHA) and Children (NHC)

The mean labeling responses from normal-hearing adults (NHA) are presented in Figure 7, and the mean labeling responses from normal-hearing children (NHC) in Figure 8. Each figure indicates percent /p/ responses as a function of burst frequency spectrum, and the figure legend represents type of formant transition (/p/-like, neutral, and /t/-like). Specifically, the solid diamonds represent responses from stimuli with a F2 transition onset frequency value appropriate for /t/ (e.g., 1600 Hz), solid squares represent responses from stimuli with a neutral F2 transition onset frequency value (e.g., 1300 Hz), and solid triangles represent responses from stimuli with a F2 transition onset frequency value appropriate for /p/ (e.g., 800 Hz). Figures 7 and 8 show clearly defined categories for both best exemplar voiceless stop sounds (e.g. /p/ burst with /p/ F2 transition stimulus and /t/ burst with /t/ F2 transition stimulus). In comparing Figures 7 and 8, the labeling functions from the normal-hearing children (NHC) are steeper and with fewer separations than those of the normal-hearing adults (NHA), suggesting less weight placed upon the F2 onset transition cues.

The analyses were performed as in Experiment I : (1) a three-way analysis of variance (ANOVA) to determine group differences, and (2) a determination of relative cue weights within groups using the ANOVA model (Hedrick & Younger, 2001, 2003, 2007). The responses were arcsine-transformed, and then entered as the dependent variables in the three-way ANOVA. The within factors for this analysis were the two cues (burst and transition) and the between factor was listener group. The summary of this analysis is presented in Table 10. Each cue shows a significant main effect, and there

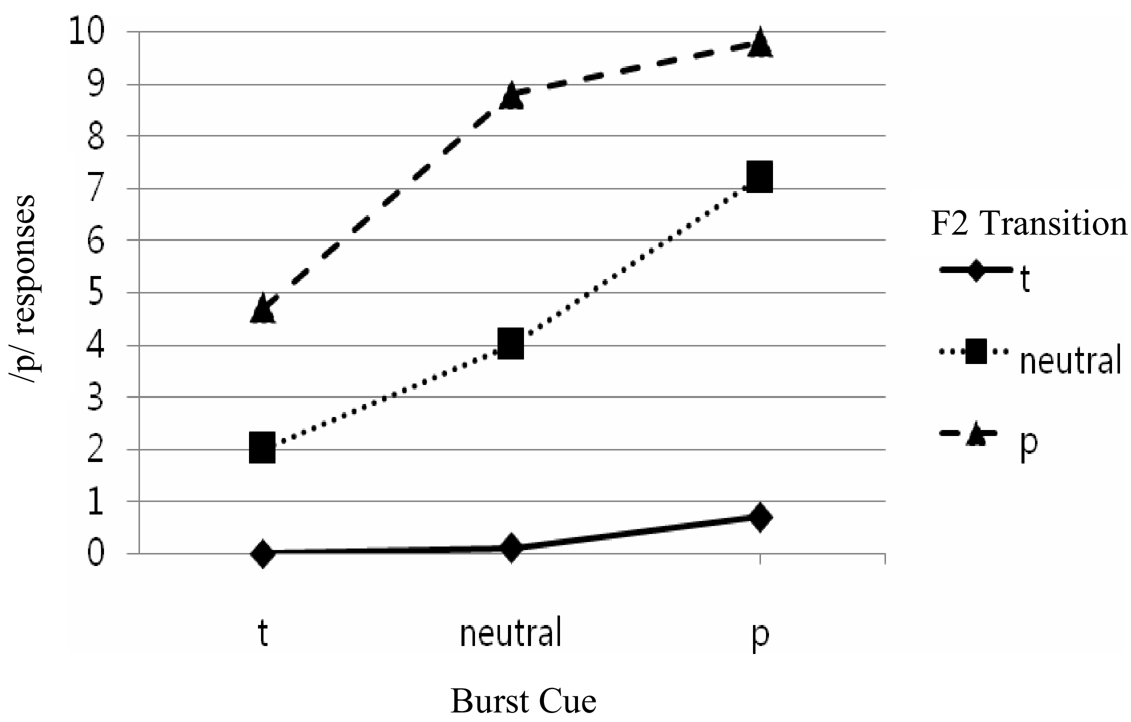

Figure 7: Mean /p/ responses from the NHA group plotted as a function of burst cue. The legend indicates that diamonds represent responses from stimuli with a F2 transition onset frequency value for /t/, squares represents responses from stimuli with a neutral F2 transition onset frequency value, and triangles represent responses from stimuli with a F2 transition onset frequency value for /p/.

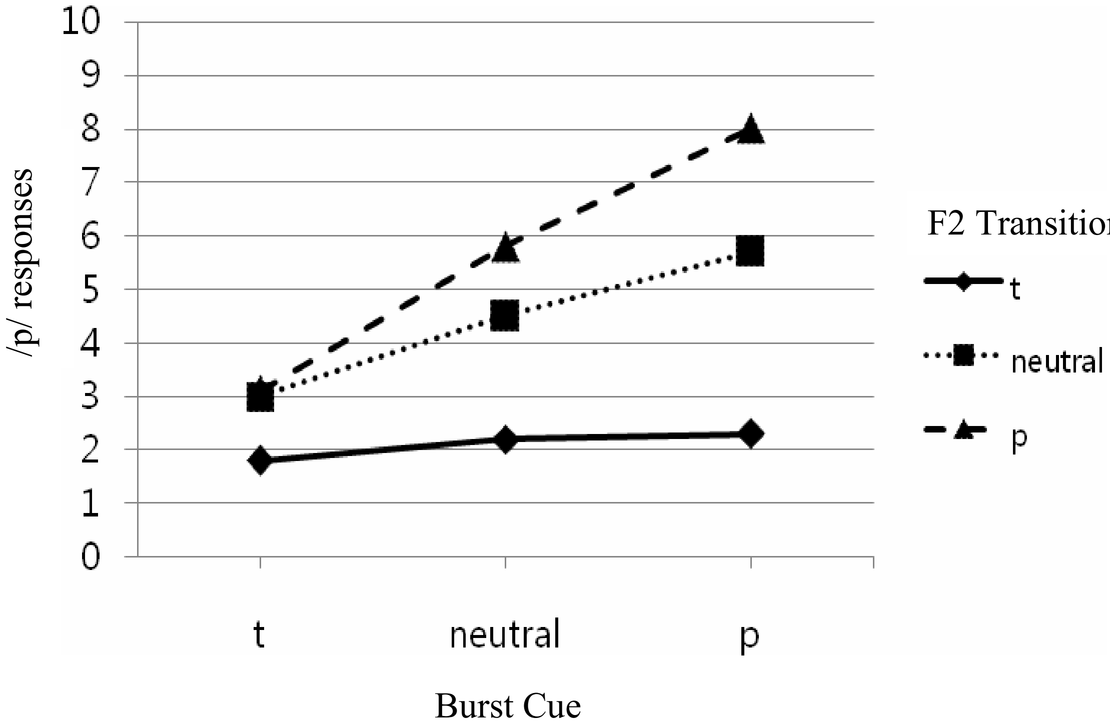

Figure 8: Mean /p/ responses from the NHC group plotted as a function of burst cue. The legend indicates that diamonds represent responses from stimuli with a F2 transition onset frequency value for /t/, squares represents responses from stimuli with a neutral F2 transition onset frequency value, and triangles represent responses from stimuli with a F2 transition onset frequency value for /p/.

Table 10: Results from the Three-way ANOVA Using Huynh-Feldt Corrections for NHA and NHC in Voiceless Stop Perception

Factor	Degree of Freedom	F-ratio	Significant P-value
Trans	2.000	95.371	.000*
Trans X Group	2.000	15.465	.000*
Burst	1.969	50.804	.000*
Burst X Group	1.969	2.822	.073
Trans X Burst	4.000	9.815	.000*
Trans X Burst X Group	4.000	1.479	.217
Group	1.000	.010	.922

*p<.05
The two within subjects factors were formant transition (Trans) and Burst frequency (Burst) cues and the between-subject factor was listener group (Group).

are significant two-way interactions involving burst cues by transition cues and transition cues by groups. To explore the two-way interaction, one-way ANOVAs were performed for each CV stimulus to distinguish any differences between the two groups. The summary of this analysis is presented in Table 11. A Holm's Bonferroni procedure was used to control for Type I error associated with multiple testing. A familywise error rate of .05 was adopted. These results indicate that four out of nine stimuli were significantly different between the NHA and NHC groups. Specifically, two exemplars, /p/ and /t/ with neutral transition cue, were significantly different between the two groups, suggesting the NHC group has less ability to label voiceless stop consonants than the NHA group when stimuli with neutral transition were presented. In addition, if stimuli have neutral transition cues, the NHC group did not use burst cues as did the NHA group (e.g., PBNT and TBNT).

To further analyze these results quantitatively, relative perceptual weights were given to the transition and burst cues and their interaction and were calculated using the ANOVA model (Hedrick and Younger, 2001, 2003, 2007). These weights are presented in Table 12 and listed as the proportion of variance accounted for by the cue. There was a greater degree of weighting on the transition cues than burst cues in the NHA and NHC groups. In addition, the proportions of weight placed on the burst cues were similar to one another (14% for NHA vs. 17% for NHC), and there were no significant differences in the three-way ANOVA results. However, the proportions of weighting placed on the transition cues were significantly different between the two groups, with the NHA group showing 61%, and the NHC group 36%. Results showed relatively small proportions of variance accounted for by integration of cues by the two groups (5% for NHA vs. 7% for

Table 11: Summary of One-way ANOVA at Each CV Stimulus for NHA and NHC Groups

Transition	Burst	F-ratio	P-value	Adjusted P value
/p/	p-like	25.400	.000	.000*
	Neutral	1.724	.205	.616
	t-like	3.513	.076	.382
Neutral	p-like	14.847	.001	.008*
	Neutral	.146	.706	.706
	t-like	9.258	.007	.040*
/t/	p-like	2.205	.154	.615
	Neutral	1.406	.250	.615
	t-like	13.329	.002	.012*

*p< .05

Table 12: Proportion of Variance Accounted for by Burst and Formant Transition Cues, and the Interaction or Integration of the Cues

Cues	NHA	NHC	CI
Burst	14*	17*	11*
Transition	61*	36*	29*
Integration	5*	8*	3
Total	80	51	43

* means significant variance accounted for (p<.05)

NHC). These results indicate a developmental pattern in transition cue for voiceless stop consonant perception.

Normal hearing children (NHC) and Children wearing cochlear implants (CI)

The same analyses were performed on the data of normal-hearing children (NHC) and children wearing cochlear implants (CI). The mean labeling responses from children wearing cochlear implants is presented in Figure 9. In comparing Figures 8 and 9, the labeling functions from the CI group are flatter than those of the NHC group, suggesting that less weight was placed upon the burst cues.

In order to determine the weighing of each cue, a three-way ANOVA was calculated. The within factors for this analysis were the two cues and the between factor was listener group. The summary of this analysis is presented in Table 13. It should be noted that each cue shows a significant main effect, but there were no group effects, or interaction effects.

The proportion of variance accounted for by each cue for each group is shown in Table 12. For both groups a greater degree of weighting was placed on the transition cues than on the burst cues. There were no significant differences between the NHC and CI groups. However, the interaction is not significant for the CI group. Total variance accounted for by the model was greater in the NHC group than in the CI group (51% for NHC vs. 43% for CI group).

Summary of Results in Experiment II

1. There was significantly different cue weighting on transition cues between the NHA and the NHC groups; however, no significant differences were found between NHC and CI groups.

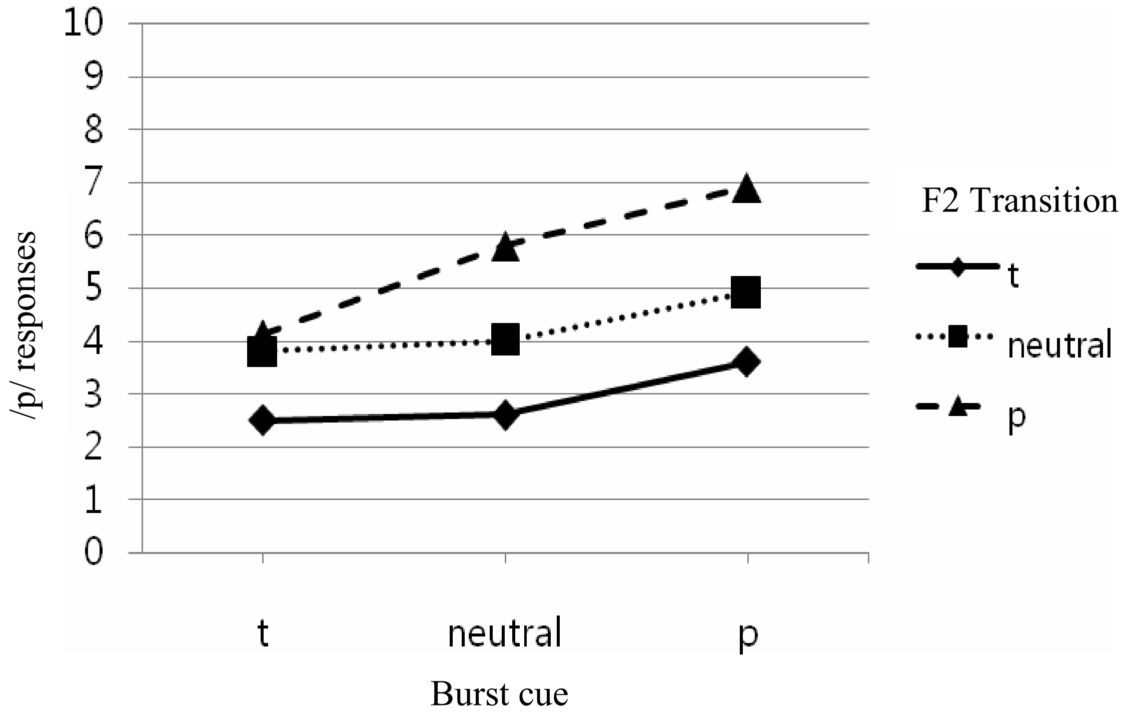

Figure 9: Mean /p/ responses from the CI group plotted as a function of burst cue. The legend indicates that diamonds represent responses from stimuli with a F2 transition onset frequency value for /t/, squares represents responses from stimuli with a neutral F2 transition onset frequency value, and triangles represent responses from stimuli with a F2 transition onset frequency value for /p/.

Table 13: Results from the Three-way ANOVA Using Huynh-Feldt Corrections for NHC and CI in Voiceless Stop Perception

Factor	Degree of Freedom	F-ratio	Significant
Trans	1.754	36.374	.000*
Trans X Group	1.754	1.833	.181
Burst	1.943	25.689	.000*
Burst X Group	1.943	1.746	.191
Trans X Burst	3.756	3.492	.014*
Trans X Burst X Group	3.756	.922	.452
Group	1.000	.518	.481

*p<.05

The two within subjects factors were formant transition (Trans) and burst frequency (Burst) cues and the between-subject factor was listener group (Group).

2. There was a developmental pattern in total variance accounted for by burst, transition, and integration cues (NHA>NHC, CI).

CHAPTER V

DISCUSSION

The aim of this study was to determine the speech weighting strategies used by children with normal hearing and children wearing cochlear implants for fricative consonant syllable and voiceless stop consonant syllables using the ANOVA model (Hedrick and Younger, 2001, 2003, 2007).

Experiment I: Fricative noise consonant perception

Normal-hearing Adults(NHA) and Children(NHC)

In Experiment I, fricative noise consonant continua were used. Fricative noise spectrum pole frequency and F2 onset transition cues were manipulated; three steps of fricative spectrum frequency and three steps of F2 onset frequency were used for cues. Each stimulus consisted of one fricative spectrum cue and one transition cue. It has been the usual practice in previous research to manipulate more than several steps (e.g., seven-nine steps) of fricative spectrum cues, whereas only two steps of F2 onset frequencies were used or vice versa. In this study, the manipulation steps were the same (three and three) to investigate the effect of transition and fricative spectrum cues equally. A total of nine stimuli were used for the experiment. The stimuli used in this study presented clear phonemic categories. In addition, the ANOVA model (Hedrick and Younger, 2001, 2003, 2007) provided relative weighting proportions in fricative consonant continua. The results from the ANOVA model indicated that for adults, fricative spectrum cues accounted for 84% of response variance, and in children, 75%. Also, there was an appreciable different cue weighting on spectrum cues between the two groups.

Results from this study were consistent with the findings of the previous study of Hedrick, Bahng, and von Hapsburg (submitted); that used fricative consonant continua similar to those of this study except for the number of steps in fricative spectrum cues and formant transition cues. In the previous study (Hedrick et al., submitted), seven steps of frication and two steps of transition cues were manipulated, and the ANOVA model was also used for calculation of proportion of variance accounted for by each cue. The bulk of the weighting on the frication spectrum cues (86% for adults vs. 50% for children) and relatively small on the transition cues (7% for adults vs. 9% for children) were revealed. There was a significant difference between groups in frication spectrum cue weighting, but not for transition cue weighting. Even though the number of manipulation steps was different, the results of the current study having an equal number of frication and transition values are similar to previous studies having different number of frication and transition values. This result showed that the number of manipulation steps for cues did not affect proportion of each cue weighting.

In a series of studies regarding cue weighting strategies in adults and children (Nittrouer & Crowther, 1998; Nittrouer, 1992, 1996; Nittrouer & Miller, 1997), slopes of labeling function and 50% phonemic boundaries were used for calculating the differences between groups. This method can provide group differences for each cue; however, it cannot provide differences between two cues within a group. In other words, it cannot explain what degree of cue weighting is assigned each cue or indicate which cue is salient for phonemic decision. Also, in one study (Nittrouer, 2002) rather than analyzing slopes and phonemic boundaries, the partial correlation coefficient analysis method was used to calculate cue weighting, thus providing the estimation of relative weights assigned to the fricative noise cues and formant transition cues. The results from one experiment (Nittrouer, 2002, reanalyzed the experiment I in Nittrouer & Miller, 1997) with an experiment setting similar to this study showed that adults placed more weight on fricative noise cues (0.826) than 7-year-old (0.770) and 4-year-old (0.683) groups, and children's groups (0.459 for 4.5 years-old-group and 0.366 for 7-years-old group) focused on formant transition cues more than did adult group (0.324). The age effect was significant for both cues. It was not clear whether there was a significant difference between 7-year-olds groups and adults group. It is possible that there may not be a significant difference between adults and children on transition cue weighting (0.366 vs. 0.324). However, this method cannot provide proportions of cue weighting, so it cannot be directly compared to the results of the current study. Except for the results of this experiment (Nittrouer, 2002), the rest of the experiments in Nittrouer's (2002) study showed that relative weights assigned to transition cues were similar or more than for fricative spectrum cues. Also, children focused significantly more on transition cues than adults did (Nittrouer, 2002, Table II, IV, VI), supporting the DWS (Developmental Weighting Shift) hypothesis. However, stimuli in each experiment were designed differently; hybrid/synthesized stimuli and different kind of fricative consonants (e.g., /f/ – /Θ/ continua) were used.

The results of the ANOVA model in present study were partly in accord with the DWS hypothesis, that suggests that the informational aspects of the signal that are weighted change substantially as children gain language experience (e.g. Nittrouer, 2002). Results from this study can be explained by the auditory sensitivity hypothesis, which suggests that children focus on the most salient cues, those that are louder, longer and more spectrally informative cues (Sussman, 1993, 2001). In the findings of the current study, both groups weighted more heavily on the fricative spectrum cue than the transition cues. Also, adult groups focused significantly more on the fricative spectrum cues than did the children's group, but the degree of transition cue weighting was not insignificant. However, results in the adult groups did not support the auditory sensitive hypothesis framed by Sussman (1993b, 2001), because adult group could not use dynamic cues better than children. Again, this study was designed differently than that of Sussman (1993b, 2001); in that study, CVC syllables were used for vowel identification.

To summarize, the results of the current study suggest that there is a developmental pattern for weighting on salient cues for phonemic decision. Also, these results cannot be fully explained by the DWS or by the auditory sensitivity hypothesis as framed by Sussman (1993b, 2001).

Normal-hearing Children (NHC) and Children Wearing Cochlear Implants (CI)

The current study compared the cue weighting strategies for fricative perception in normal-hearing children and in children wearing cochlear implants. The relative weights assigned to each cue were calculated using the ANOVA model (Hedrick & Younger, 2001, 2003, 2007). Results from the ANOVA model indicated that fricative spectrum cues accounted for 75% of response variance for NHC, but children wearing cochlear implants, only for 39%. This was a significant difference between the two groups, as shown by the ANOVA model. However, normal-hearing children did not focus significantly more on transition cues than did children wearing cochlear implants

(4% vs. 11%). In addition, integration of cues was significant in normal-hearing children, but not significant in children wearing cochlear implants.

The findings of this study corresponded with those of the previous study (von Haspburg, Bahng, and Hedrick, submitted). In the previous study, results showed that the bulk of the weighting was on frication spectrum cues (50% for normal-hearing children vs. 26% for children wearing cochlear implants) and relatively minor on the transition cues (9% for normal hearing children vs. 4% for children wearing cochlear implants). There was a significant difference between two children groups on fricative spectrum cue weighing, but there was no difference on transition cue weighting.

The results from the current study were similar to the reported in Pittman and Stelmachowicz (2002)'s study. Normal-hearing children and adults and hearing-impaired children and adults wearing hearing aids participated in that study. Hearing-impaired participants had mild-to-moderate flat hearing sensitivity configurations. The stimuli were natural voice /uʃ/- /us/ contrasts, which were broken down as functions of stimulus segments: vowel, transition, and fricative consonant. Also, audibility was controlled for in each of the hearing-impaired groups. Correlation coefficients were calculated for perceptual weightings. Results showed that the performances were highly correlated with the fricative segments of /uʃ/ and /us/ syllables. In other words, all groups placed more weight on the fricative spectrum segment than on vowel and transition segments. However, there was no significant difference among groups. It is possible that the age of the children's groups (mean age of 10 years) contributed to this lack of difference. Perceptual weighting strategies are thought to be adult-like after the age of 8 (Sussman, 2001). Also, in the Pittman and Stelmachowicz' study (2002) presentation levels were adjusted based on hearing sensitivity for the hearing impaired groups, whereas the levels were fixed in the current study. Even though experiment designs and characteristics of groups were different across the two studies, the overall trend was similar. Both studies showed that normal-hearing children and hearing-impaired children focused on fricative spectrum cues more than any other cues for fricative consonant perception, especially for /s/ and /ʃ/.

In the current study, a language test (CELF-4®) was performed for the two children's groups. The core language scores are reported in Tables 1 and 2. The core language includes receptive language and expressive language subtests. The average standard score was 111 in the normal-hearing children's group, whereas it was 50 in the cochlear implant group. Almost all cochlear implant children were in the <1 percentile range. The language abilities of the cochlear implant group were substantially inferior to those of normal-hearing children. Nittrouer and Burton (2001) found significantly different cue weighting strategies and language assessment between non-mainstreamed hearing-impaired children and mainstreamed children. This suggested that experience with auditory signals or other language experiences might influence the ability to use appropriate cues for making phonemic decisions. In this study, the disparity in language abilities between the two groups may have led to markedly different degrees of fricative cue weighting.

Another possibility is hearing experience; even though aided hearing sensitivities of children with cochlear implants were in almost normal range and all stimuli presentation levels were audible, the perception of speech signals might not be the same as in normal-hearing children. The hearing ages (duration of amplification) were 5.5

years, including hearing aids. Cochlear implant groups have less experience listening to sounds compared to normal-hearing children. In particular, frication spectrum cues have relatively higher frequency than those of transition cues. It may be difficult for children with cochlear implants to perceive relatively high frequencies.

In conclusion, normal hearing children and children wearing cochlear implant placed more weight on fricative spectrum than transition cues. Also, the degree of fricative spectrum weightings was significantly different between the two children's groups, but that of transition cues was not. It may be that the different language ability or hearing sensitivity, and/or hearing age could account for the discrepancy in perceptual weighting in the fricative spectrum.

Experiment II: Voiceless Stop Consonant Perception

Normal- hearing Adults (NHA) and Children (NHC)

The purpose of the current study was to examine whether normal-hearing adults and normal-hearing children have different cue weighting strategies in voiceless stop consonant continua. Also, if these two groups have different cue weighting strategies, how different are they? In order to answer these questions, burst and F2 onset transition cues were used; three steps of burst amplitude change and three steps of F2 onset frequency were used for cues. Each stimulus consisted of one burst cue and one transition cue; a total of nine stimuli were used for this experiment. The analyses were performed in the same manner as in Experiment I. The ANOVA model (Hedrick & Younger, 2001, 2003, 2007) provided proportions of relative weighting on each cue in voiceless stop consonant continua. In the current study, adults and children placed more weight on transition cues than on burst cues. The group of normal-hearing adults gave significantly more weight to the transition cues (61%) than did the normal-hearing children's group (36%). Degrees of weighting on burst cues were not significantly different between the two groups; for the normal-hearing adult group, 14% and the normal-hearing children group, 17%. In addition, a small but significant variance was accounted for by integration of cues (burst + transition); 5% and 8%, respectively. Total variance accounted for was 80% for NHA, and 61% for NHC. This result indicated that adults used more consistently the salient cue for phonemic decisions than did children. Taken together, transition cues are considered to be the primary cues and burst cues the secondary cues for voiceless stop consonant perception. Developmental differences were observed in transition cues, which are the salient cues for making phonemic decisions in voiceless stop consonant continua.

The results of the ANOVA model provided significant proportions of variance explained by the interaction of the burst and formant transition cues in both adults and children. The interaction can be defined as the perception of one cue depending on the value of another cue (Hedrick & Younger, 2001, 2003, 2007), and thus may provide a crude estimate of cue integration. In this study, results showed that the proportion of variance accounted for by the integration of cues was similar for NHA and NHC. This conclusion support the supposition that the integration of cue is important for perceiving stop consonants (e.g., Parnell & Amerman, 1978; Ohde et al., 1995). However, studies (e.g., Ohde et al., 1995) also showed that the ability to integrate cues followed a developmental pattern, but a developmental pattern was not found in this study.

The findings in this study are consistent with previous reports of stop consonant perception (Blumstein, Isaacs, & Mertus, 1982; Wally & Carrell, 1983; Ohde & Haley, 1997). Blumstein et al. (1982) reported that the second formant transition cue rather than the gross shape of spectrum cue is dominant for identification of stop consonants. Wally and Carrell (1983) also indicated the importance of the role of transition cues for stop consonant identification in adults and 5-year old children. Age difference in transition cue weighting was not reported in either study. Ohde and Haley (1997) reported that formant transition cues were the developmentally salient cues in children 3- and 4-years old only in [g] context. In the study performed by Ohde and Haley (1997), moving and straight transition cues were used. However, there was frequency information in straight transition cues. In this case, frequency information would help to perceive stimuli, even though the stimuli had no formant moving information. It might be reasoned that the findings are restricted in the velar context. In addition, Hicks and Ohde (2005) showed different results regarding the developmental difference in transition cue weighting. They investigated different cue weighting strategies in adults and 4-5 year-old children using /ba/-/wa/ continua. In this study, results showed that children and adults used transition cues as primary cues. Also, children were more biased toward transition cues than adults because the change of frequency information of the transition cue affected phonemic boundaries more for children than adults. This result was consistent with the DWS hypothesis (Nittrouer, 1992), but did not match the results of the current study. However, Hicks and Ohde (2005) used stop-glide continua, and stimuli were manipulated by frequency of transition and duration of transition with or without burst cues.

In voiceless stop consonant perception, there was a developmental pattern on the primary cue, which was the transition cue. However, there was no age effect on secondary cue – burst cue. These results also are not consistent with the DWS hypothesis.

If the results followed the DWS hypothesis, children would focus on transition cues more than adults. However, the results showed NHA weighted more on transition cue than NHC did. For both fricative and stop consonant stimuli, NHA, NHC and CI all weighted the longest duration cue the most. For fricatives, the longest duration cue is the frication spectrum; for stops, the longest duration cue is the formant transition. So, it would appear that all groups placed the most weighted on the longer duration (or more salient) cue.

To summarize, there was a perceptual developmental pattern of weighting on the salient cue, the transition cue, for voiceless stop consonant. The burst cue is considered to be a secondary cue, and children and adults showed significant integration of cues. However, there were no significantly age effects.

Normal-hearing Children (NHC) and Children Wearing Cochlear Implants (CI)

The current study compared the cue weighting strategies for voiceless stop consonant perception in normal-hearing children and in children wearing cochlear implants. The relative weights assigned to each cue were calculated using the ANOVA model (Hedrick & Younger, 2001, 2003, 2007). Results from the ANOVA model indicated that transition cues accounted for 36% of the variance in NHC, and 29% in children wearing cochlear implants. Burst cues accounted for 17% of the variance in NHC, and in children wearing cochlear implants, 11%. These results for these two cues were not significantly different between the two groups. In addition, the integration of cues accounted for a significant proportion of the variance in NHC, but not in children wearing cochlear implants. The total proportions of variance accounted for by all cues were 51% and 40%, respectively.

Results of the current study showed that there were no cue weighting strategy differences between normal-hearing children and children wearing cochlear implants. This result corresponds with the findings of Nittrouer and Burton (2001). They investigated speech cue weighting strategies in hearing-impaired children and normal-hearing children for fricative speech perception. There were significant differences between mainstreamed children and non-mainstreamed children, but there were no significant differences between mainstreamed children and normal-hearing children in the slopes of the identification functions. These findings suggested that experience of auditory signal and language experience might affect the ability to make phonemic decisions. In the work of Nittrouer and Burton (2001), there were no marked differences in nonverbal reasoning ability, receptive vocabulary, and reading ability between the control group and the mainstreamed hearing-impaired group. Also, the PTA (Pure Tone Average) of the mainstreamed hearing-impaired group showed a moderate hearing loss. However, in the present study, even though children wearing cochlear implants received early intervention (early onset of amplification and onset of therapy) and had intensive speech and language therapy, children wearing cochlear implants groups and normal-hearing children group showed significantly different language abilities in CELF-4® (Tables 1 and 2). The findings of Experiment I indicated that children wearing cochlear implants and normal-hearing children had significantly different cue weighting strategies. These two experiments indicated that language ability might not be the only factor related to building speech cue weighting strategies.

One possibility is that developmental speech cue weighting is related to children's language production. Stop consonant production mastery happens earlier than fricative consonant production (Sander, 1972). Stop consonant /p/, nasal /m, n/, glides /w/, and fricative /h/ are mastered by 90% of children by the age of three. The next consonants /b, d, g, k/ are mastered by 90% of children by the age of four, and /t/ is mastered by 90% by the age of six. Finally, fricatives /s, ʃ/ are mastered by 90% of children some time after than six years of age. It might be possible that children wearing cochlear implants have more experience in production and perception of stop consonant sounds than any other speech sounds, and thus they build up similar perceptual voiceless stop consonant cue weighting strategy to that of normal-hearing children. This explanation might account for the differences in perceptual fricative cue weighting strategies between children wearing cochlear implants and normal-hearing children, but it may not agree with the comparisons between NHC and NHA in this study. In fact, the NHC and NHA appear closer together in Table 7, on a fricative sound that should be the last to develop. If the production explanation is correct, the children might not similar to adult perception for the fricatives (a later-developing sound) than for the stops (an earlier-developing sound).

Another possibility is that the salient cue, that is, the transition cue for voiceless stop consonant, is relatively easier to focus on than the fricative noise cue for children wearing cochlear implants. The transition cue is relatively longer than the burst cue and has relatively low frequency energy in voiceless stop consonants. In this experiment, the burst cue was manipulated by amplitude. However, this proposition does not correspond with previous reports by Hedrick and Carney (1997) and Hedrick and Younger (2001). In those previous studies, relative amplitude cues and transition cues were manipulated in voiceless stop consonant continua in assessing adult cochlear implant users (Hedrick & Carney, 1997) and adult hearing aid users (Hedrick & Younger, 2001). Results from these studies showed hearing-impaired listeners used formant transition cues differently than did normal-hearing listeners. The authors theorized that the deficit of using formant transition cue in hearing impaired listeners might be caused by misrepresentation of sounds in processing design or the problem of processing the cue in the auditory nerve. However, in both studies, participants were adults and the research used relatively old processor designs (K-AMP circuit and MPEAK strategy) for amplification. These factors might affect the differences between the results from this study and those of previous studies.

In the current study, results of the ANOVA model provided the information about proportions assigned by weighting of each cue as well as integration or interaction cues. Results showed that the integration of cues was not significant only in children wearing cochlear implants group. This result was consistent with the results of Experiment I and previous studies (Hedrick & Younger, 2001; Hedrick & Jeasteadt, 1995; Hedrick & Carney. 1997; von Hapsburg et al., submitted). This lack of integration of cues in cochlear implant users might be caused by distortion of the cochlear implant speech processor or an inability to focus on the interaction of two cues, or maybe by distorted auditory coding.

In summary, the findings from this study indicated that children wearing cochlear implant and normal-hearing children used similar perceptual cue weighting strategies, even though the language abilities of each group were different. This result showed that language ability is not the only one factor affecting speech cue weighting strategy. However, the integration cue was not significant for children wearing cochlear implants;

this may be due to a misrepresentation of sounds in the cochlear implant speech processor or maybe by distorted auditory processing.

CHAPTER VI

CONCLUSION

The current study investigated the speech cue weighting strategy in fricative noise consonant continua and voiceless stop consonant continua in normal-hearing adults, children, and children wearing cochlear implants. The ANOVA model was used for calculation of perceptual weighting in each group. Results showed that there were developmental patterns on salient cues for each continuum. In the fricative noise consonant /su/-/ʃu/ continua, both children's and adult groups focused on fricative spectrum cues more than on transition cues. Adults gave significantly more weight than children to the fricative spectrum, but there was no significant difference in transition cue weighting between adults and children. In the voiceless stop consonant /pu/-/tu/ continua, the result was consistent with those of the fricative noise consonant continua. For voiceless stop consonants, the transition cue is the salient cue. Adults gave significantly more weight than children to transition cues, but there was no significant difference in burst cue weighting between adults and children.

In Experiment I, children wearing cochlear implants and normal-hearing children showed significantly different perceptual cue weighting strategies in the fricative spectrum cue, but in Experiment II, there was no significant difference between the two groups. The language abilities of these two groups were very different from one another. Results of these two experiments indicated that there were other factors besides language ability that might affect the ability to build up speech cue weighting strategies. However, the integration of cues was significant in the normal-hearing children's group, but not significant in children wearing cochlear implants in Experiments I and II. Findings suggested that children wearing cochlear implants had difficulties in integrating the two cues.

In addition, the results from this study could not explain by DWS hypothesis. All groups weighted on longer duration cue no matter it is dynamic cue or steady-state cues in fricative consonant continua and voiceless stop consonant continua. However, the result also did not follow auditory sensitivity framed as described by Sussman (1993b, 2001), either. This hypothesis states that adults focus more on short or dynamic cues than children do. However, there was no significant difference between adults and children except primary cue.

Future Research

Future studies should focus on how speech cue weighting strategies develop in normal-hearing children as well as in hearing-impaired children. In order to better understand the development of speech cue weighting strategies, future study should investigate the following:

1. The effects of various vowel contexts on each consonant;
2. The relationship between the factors (e.g. language and speech) and speech cue weighting strategy in normal-hearing children and children wearing cochlear implants;
3. The effects of different speech processor strategies on speech cue weighting strategies in children wearing cochlear implants;
4. The effect of integration of cues on speech cue weighting strategies.

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APPENDICIES

Appendix A

This appendix lists synthetic parameter values for the /su/-like, most /shu/-like, and neutral stimuli. With the exception of T (time, in ms), columnar parameter abbreviations are taken from Klatt (1980).

Table A1. Synthesis parameters for the most /s/-like stimulus (SFST).

T	AV	AF	F0	F1	F2	F3	F4	F5	F6	A3	A4	B1	B2	B3
0	0	35	0	350	1200	2200	3700	4200	4900	60	0	65	110	140
230	0	47	130	350	1200	2200	3700	4200	4900	60	0	65	110	140
240	59	0	130	350	1200	2200	3300	4200	4900	0	0	65	110	140
305	59	0	120	350	900	2200	3300	4200	4900	0	0	65	110	140
480	45	0	100	350	900	2200	3300	4200	4900	0	0	65	110	140

Table A2: Synthesis parameters for the most /sh/-like stimulus (ʃFʃT).

T	AV	AF	F0	F1	F2	F3	F4	F5	F6	A3	A4	B1	B2	B3
0	0	35	0	350	1800	2200	3300	4200	4900	55	0	65	110	140
230	0	47	130	350	1800	2200	3300	4200	4900	55	0	65	110	140
240	59	0	130	350	1800	2200	3300	4200	4900	0	0	65	110	140
305	59	0	120	350	900	2200	3300	4200	4900	0	0	65	110	140
480	45	0	100	350	900	2200	3300	4200	4900	0	0	65	110	140

Table A3: Synthesis parameters for the neutral stimulus (NFNT).

T	AV	AF	F0	F1	F2	F3	F4	F5	F6	A3	A4	B1	B2	B3
0	0	35	0	350	1500	2200	2950	4200	4900	0	60	65	110	140
230	0	47	130	350	1500	2200	2950	4200	4900	0	60	65	110	140
240	59	0	130	350	1500	2200	3300	4200	4900	0	0	65	110	140
305	59	0	120	350	900	2200	3300	4200	4900	0	0	65	110	140
480	45	0	100	350	900	2200	3300	4200	4900	0	0	65	110	140

Appendix B.

This appendix lists synthetic parameter values for the /pu/-like, most /tu/-like, and neutral stimuli. With the exception of T (time, in ms), columnar parameter abbreviations are taken from Klatt (1980).

Table B1: Synthesis parameters for the most /pu/-like stimulus (PBPT).

T	AV	AF	AH	F0	F1	F2	F3	F4	F5	F6	A1	A2	A3	A4	A5	A6	B1	B2	B3
0	0	0	0	0	350	800	2200	3300	4200	4900	0	0	0	0	0	0	65	110	140
165	0	0	0	0	350	800	2200	3300	4200	4900	0	0	0	0	0	0	65	110	140
170	0	35	0	0	350	800	2200	3300	4200	4900	30	30	45	45	30	30	65	110	140
185	0	55	35	0	350	800	2200	3300	4200	4900	30	30	45	45	30	30	65	110	140
190	0	55	47	0	350	800	2200	3300	4200	4900	30	30	45	45	30	30	65	110	140
230	43	0	23	130	350	900	2200	3300	4200	4900	0	0	0	0	0	0	65	110	140
270	59	0	0	120	350	900	2200	3300	4200	4900	0	0	0	0	0	0	65	110	140
480	45	0	0	100	350	900	2200	3300	4200	4900	0	0	0	0	0	0	65	110	140
485	0	0	0	0	350	900	2200	3300	4200	4900	0	0	0	0	0	0	65	110	140

Table B2: Synthesis parameters for the most /tu/-like stimulus (TBTT).

T	AV	AF	AH	F0	F1	F2	F3	F4	F5	F6	A1	A2	A3	A4	A5	A6	B1	B2	B3
0	0	0	0	0	350	1600	2200	3300	4200	4900	0	0	0	0	0	0	65	110	140
165	0	0	0	0	350	1600	2200	3300	4200	4900	0	0	0	0	0	0	65	110	140
170	0	35	0	0	350	1600	2200	3300	4200	4900	30	30	45	59	30	30	65	110	140
185	0	40	35	0	350	1600	2200	3300	4200	4900	30	30	45	59	30	30	65	110	140
190	0	40	47	0	350	1600	2200	3300	4200	4900	30	30	45	59	30	30	65	110	140
230	43	0	23	130	350	900	2200	3300	4200	4900	0	0	0	0	0	0	65	110	140
270	59	0	0	120	350	900	2200	3300	4200	4900	0	0	0	0	0	0	65	110	140
480	45	0	0	100	350	900	2200	3300	4200	4900	0	0	0	0	0	0	65	110	140
485	0	0	0	0	350	900	2200	3300	4200	4900	0	0	0	0	0	0	65	110	140

Table B3: Sythesis parameters for the neutral stimulus (NBNT).

T	AV	AF	AH	F0	F1	F2	F3	F4	F5	F6	A1	A2	A3	A4	A5	A6	B1	B2	B3
0	0	0	0	0	350	1300	2200	3300	4200	4900	0	0	0	0	0	0	65	110	140
165	0	0	0	0	350	1300	2200	3300	4200	4900	0	0	0	0	0	0	65	110	140
170	0	35	0	0	350	1300	2200	3300	4200	4900	30	30	45	49	42	30	65	110	140
185	0	55	35	0	350	1300	2200	3300	4200	4900	30	30	45	49	42	30	65	110	140
190	0	55	47	0	350	1300	2200	3300	4200	4900	30	30	45	49	42	30	65	110	140
230	43	0	23	130	350	900	2200	3300	4200	4900	0	0	0	0	0	0	65	110	140
270	59	0	0	120	350	900	2200	3300	4200	4900	0	0	0	0	0	0	65	110	140
480	45	0	0	100	350	900	2200	3300	4200	4900	0	0	0	0	0	0	65	110	140
485	0	0	0	0	350	900	2200	3300	4200	4900	0	0	0	0	0	0	65	110	140

Appendix C

Informed Consent Form (Adults)

Title: Acoustic Cue Weighting in Children Wearing Cochlear Implants

You are being asked to participate in a study of speech perception. The goal of this study is to learn what acoustic information persons use to perceive speech sounds.

Procedures

To take part in this study, you should be 1) 18-40 years old, 2) a native speaker of English and 3) have normal hearing. If you take part in this study, you will receive a free hearing test, unless there is a record of an audiogram within the past year. Following the hearing test, you will be given a hearing history form to complete. As a participant in this study, you will be asked to identify some consonant sounds. After listen to each stimulus, you need to select one of two options using the respond box. If you do not meet the criteria for the study or are unable to perform the listening task, you will be unable to complete the study and your participation will end at this point. Completion of this experiment will take approximately 30 minutes. If you will need a break, you can ask an investigator.

Potential risk or discomfort

There are no significant risks associated with participation in this study.

Benefits

You will get free hearing test.

Assurance of confidentiality

Information learned about you will be kept confidential. When referring to data collected from presentations or publications, we will use a code number and will not use your name. This informed consent form will be kept in a locked file cabinet in South Stadium Hall at the University of Tennessee for three years. After three years, the consent form will be destroyed.

Alternatives

You do not have to take part in this study if you do not want to. Your participation or non-participation in this project will in no way affect any future treatment or services you seek in any department at the University of Tennessee at any time.

Right to withdraw

You can stop taking part in the study at any time, even after you sign this agreement. If you want to stop taking part in the study, simply tell us. There is no penalty for quitting.

COMPENSATION

You will receive $10 upon completion of the study.

HIPAA

Under federal privacy regulations, you have the right to determine who has access to your personal health information (called "protected health information" or PHI). PHI collected in this study may include your hearing health history and copies of medical records pertaining to your hearing health that you have authorized. By signing this consent form, you are authorizing the research team at The University of Tennessee to have access to your PHI collected in this study, and to receive your PHI from your physician and/or other facilities where you have received hearing health care. Your PHI will not be used or disclosed to any other person or entity, except as required by law, or authorized oversight of this research study by other regulatory agencies, or for other research for which the use and disclosure of your PHI has been approved by the IRB. Your PHI will be used only for the research purposes described in this consent form. Your PHI will be used until the study is completed. You may cancel this authorization in writing at any time by contacting the principal investigator listed at the bottom of this consent form. If you cancel the authorization, continued use of your PHI is permitted if it was obtained before the cancellation and its use is necessary in completing the research. However, PHI collected after your cancellation may not be used in the study. If you refuse to provide this authorization, you will not be able to participate in the research study. If you cancel the authorization, then you will be withdrawn from the study. Finally, the federal regulations allow you to obtain access to your PHI collected or used in this study.

Authorization

I have read the above information and agree to participate in this study. I have received a copy of this form.
Participant's name (print) ____________________________

Participant's signature ___________________________
Date___________________

Investigator's assurance

The individuals whose names appear below are responsible for carrying out this research program. They will assure that all questions about this research program are answered to the best of their ability. They will assure that you are informed of any changes in the procedures or the risks and benefits if any should occur during or after the course of this study. They will assure that all information remains confidential. If you have questions about your rights as a participant, contact the Compliance Section of The Office of Research at 865-974-3466.

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Appendix D

Parental Informed Consent Form

Title: Acoustic Cue Weighting in Children Wearing Cochlear Implants

Your child is being asked to participate in a study of speech perception. The goal of this study is to learn what acoustic information persons use to perceive speech sounds.

Procedures

To take part in this study, your child should be 1) 4-8 years old, 2) a native speaker of English and 3) have normal hearing or a cochlear implant. If your child takes part in this study, your child will receive a free hearing test. Following the hearing test, you will be asked to fill out a short history form regarding your child's hearing. As a participant in this study, your child will be asked to identify some consonant sounds. After each stimulus, your child needs to select the appropriate picture card. If your child does not meet the criteria for the study or is unable to perform the listening task, your child will be unable to complete the study and their participation will end at this point. Completion of this experiment will take approximately 1 hour, and your child will be given breaks of two to five minutes for every ten to fifteen minutes of listening.

Potential risk or discomfort

There are no significant risks associated with participation in this study.

Benefits

Your child will get free hearing test, unless there is a recent audiogram within two past years.

Assurance of confidentiality

Information learned about your child will be kept confidential. When referring to data collected from your child in presentations or publications, we will use a code number and will not use your child's name. This informed consent form will be kept in a locked file cabinet in South Stadium Hall at The University of Tennessee for three years. After three years, the consent form will be destroyed.

Alternatives

Your child does not have to take part in this study if your child does not want to. Your child's participation or non-participation in this project will in no way affect any future treatment or services your child seeks in any department at The University of Tennessee at any time.

Right to withdraw

Your child can stop taking part in the study at any time, even after you sign this agreement. If your child wants to stop taking part in the study, simply tell us. There is no penalty for quitting.

COMPENSATION

Your child will receive a $10 Toys-r-US gift card and t-shirt for participation in this study. If your child does not complete the session, your child will still get the $10 Toys-r-US gift card.

HIPAA

Under federal privacy regulations, you have the right to determine who has access to your personal health information (called "protected health information" or PHI). PHI collected in this study may include your hearing health history and copies of medical records pertaining to your hearing health that you have authorized. By signing this consent form, you are authorizing the research team at The University of Tennessee to have access to your PHI collected in this study, and to receive your PHI from your physician and/or other facilities where you have received hearing health care. Your PHI will not be used or disclosed to any other person or entity, except as required by law, or authorized oversight of this research study by other regulatory agencies, or for other research for which the use and disclosure of your PHI has been approved by the IRB. Your PHI will be used only for the research purposes described in this consent form. Your PHI will be used until the study is completed. You may cancel this authorization in writing at any time by contacting the principal investigator listed at the bottom of this consent form. If you cancel the authorization, continued use of your PHI is permitted if it was obtained before the cancellation and its use is necessary in completing the research. However, PHI collected after your cancellation may not be used in the study. If you refuse to provide this authorization, you will not be able to participate in the research study. If you cancel the authorization, then you will be withdrawn from the study. Finally, the federal regulations allow you to obtain access to your PHI collected or used in this study.

Authorization

I have read the above information and agree my child to participate in this study. I have received a copy of this form.
Participant's parent name (print) ____________________________

Participant's parent signature ___________________________
Date___________________

Investigator's assurance

The individuals whose names appear below are responsible for carrying out this research program. They will assure that all questions about this research program are answered to the best of their ability. They will assure that you are informed of any changes in the procedures or the risks and benefits if any should occur during or after the course of this study. They will assure that all information remains confidential. If you have questions about your rights as a participant, contact the Compliance Section of The Office of Research at 865-974-3466.

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Appendix E (For Normal Hearing Children and Adults)

Audiologic History

ID:______________
Date of Birth (Age): __________(______)
Date:___________________

1. Have you (your child) had a significant history of ear problems?
   ______yes ________no

2. If you (your child) answered yes to question one, please check all that apply

   ___ Middle ear infections/pain (how often?_______per 1 year?)
   ___ Pressure equalizing tubes placed in your ears
   ___ Dizziness
   ___ Noticeable ringing in your ears
   ___ Trauma to the ear: Explain____
   ___ Accidents/Head Injury
   ___ Noise exposure
   ___ Other, please specify
   ____
   ____

3. Have you (your child) had any ear surgery? If so, for what reason?

4. Have you (your child) had a serious illness for which you took long-term antibiotics?

5. Is there a family history of hearing loss?

6. Have you (your child) ever sustained or been diagnosed with any of the following? (Check all that apply)

   ____Head trauma with loss of counsciousness
   ____Brain injury
   ____Learning Disabilities
   ____Speech disorders (not related to accent reduction)
   ____ Language Disorders
   ____Other, please specify
   ____
   ____
   ____

Appendix F (For Cochlear Implant Children)

Audiologic History

ID:______________
Date of Birth:_____________
Date:___________________

1. How old was your child when the hearing loss was first identified?
2. Do you know the cause of hearing loss? If so, what is it?
3. Does your child have visual, motor, or other developmental problems? If so, please explain:
4. At what age did your child first get fitted with hearing aids?
5. At what age did your child get implanted with a cochlear implant?
6. How long did your child use hearing aids before getting the implant?
7. Does your child wear a hearing aid in the non-implanted ear?
8. At what age did your child start to receive speech/language therapy?
9. How many times per a week does your child receive speech/language therapy?
10. What type of school does your child attend? (example: regular classroom, class for the hearing impaired in a regular school, school for the deaf)
11. What grade is your child in at school?
12. What is your child's reading level at this moment? (pre-literacy, 1^{st} grade level, 2^{nd} grade level, 3^{rd} grade level, etc.)

VITA

Junghwa Bahng was born in Seoul, Korea in 1976 and was raised in Seoul, Korea. Junghwa graduated high school from Banpo high school in 1995 and continued her education at The Catholic University of Korea, receiving a Bachelor of Arts in French Literature and Language in 2000. Junghwa then went to The Hallym University in Korea, where she received her Master's of Science in Audiology in 2002. Junghwa moved to The University of Tennessee at Knoxville in the United States, where she received her Doctor of Philosophy in Speech and Hearing Science in 2008.