1-1-2011

Audibility as a Predictor of Speech Recognition and Listening Effort

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AUDIBILITY AS A PREDICTOR OF SPEECH RECOGNITION

AND LISTENING EFFORT

by

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A DISSERTATION

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Doctor of Philosophy

Major: Human Sciences

Under the Supervision of Professors Stephen J. Boney and Patricia G. Stelmachowicz

Lincoln, Nebraska

May, 2011

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Two studies were conducted to evaluate how audibility influences speech recognition and measures of working memory in children with normal hearing. Specifically, audibility limitations related to background noise and limited bandwidth were analyzed, as these factors are characteristic of the listening conditions encountered by children with hearing loss who wear hearing aids.

In the first study, speech recognition was measured for 117 children and 18 adults with normal hearing. Stimulus bandwidth and the level of background noise were varied systematically in order to evaluate predictions of audibility based on the Speech Intelligibility Index. Results suggested that children with normal hearing required greater audibility to reach the same level of speech understanding as normal-hearing adults. However, differences in performance between adults and children did not vary across frequency bands as anticipated.

In the second study, 18 children with normal hearing completed two tasks of working memory to examine how background noise and limited bandwidth might limit memory processes in children. In a non-word repetition task, significant reductions in speech recognition and increases in response time were observed for both the noise and limited bandwidth conditions. These results suggest that listening effort increased and phoneme recall decreased when the speech signal was degraded. For recall of real words, no differences in recognition were observed for two conditions with the same signal-to-noise ratio but differing bandwidths. However, recall was significantly inhibited in the limited bandwidth condition, supporting the hypothesis that a limited bandwidth may negatively impact working memory performance in children, even when recognition is preserved.

Collectively, these studies suggest that methods of calculating audibility based on adults are likely to be inadequate for predicting speech recognition and listening effort for children. Models of audibility that incorporate the linguistic and cognitive dynamics of children are necessary to maximize communication outcomes for children with hearing loss.

Acknowledgements

Completing this project has been a challenging and rewarding experience that I could not have completed without substantial support from a wonderful group of family, friends, colleagues and mentors. I can't even begin to express my gratitude to my wife and best friend, Becky. I appreciate the sacrifices she has made to help me through this, as well as her love and support. I am grateful for my children Liam and Anna, who both were born during my program. My parents, Tom and Janan McCreery, also deserve more thanks than I can express. Fostering creativity, promoting critical thinking, and providing unconditional love and support were just a few of the things they have done throughout my life that helped me in this endeavor.

My doctoral committee members have all contributed to my development as a researcher. I owe special thanks to my mentor Dr. Pat Stelmachowicz. Pat gave me the opportunity to work in her lab, write my own grant, learn how to do research, and become a better writer. For all of this, I am eternally thankful. I have also had the benefit of the mentorship and support of Dr. Stephen Boney, not only on this project, but from the time I was a clinical student over a decade ago. Dr. Tom Carrell and Dr. T. Newell Decker were also both instrumental in my training as an audiologist and as a researcher. Dr. Nicholas Smith has contributed a very valuable and much-needed perspective from his background in developmental psychology. The theoretical principles of relating audibility to communication development were greatly enhanced due to the contributions of Dr. Tiffany Hogan.

Finally, I wish to thank all the individuals who provided input and technical support to the research project. My colleagues in the Hearing and Amplification Research Lab (HARL) at Boys Town National Research Hospital all supported this work in various ways. The HARL contributors were Merry Spratford, Beth Heinrichs, John Andre, Dawna Lewis, Judy Kopun, Jody Spalding, Brenda Hoover and Kanae Nishi. Computer programming support from Joshua Alexander, Marc Brennan, and Prasanna Aryal made data collection and analyses possible.

Grant Information

This research was supported by grants from the National Institutes of Health (NIH) National Institute for Deafness and Communication Disorders (NIDCD) F31 DC010505 (Pre-doctoral fellowship) and P30 DC004662 (Human Research Subjects Core).

Table of Contents

List of Figures

List of Tables

CHAPTER 1: INTRODUCTION

Overview

The primary negative perceptual consequence of hearing loss is the loss of audibility for speech. The ability to hear the acoustic cues that comprise spoken language is essential for developing and maintaining communication. The long-term effects of limited audibility due to hearing loss are well-documented. Children with hearing loss that occurs before or during language development face significant challenges in the development of speech and language skills without early detection and intervention (Moeller, 2000). Even for adults with mature communication skills, hearing loss can lead to decreased participation in social activities and increased likelihood of depression (National Council on Aging, 2000). Fortunately, outcomes related to hearing loss can be substantially improved for both children and adults by restoring access to speech and language via hearing aids and/or other hearing assistance technology. For example, Chisolm et al. (2007) completed an evidence-based systematic review of the effects of hearing aids on health-related quality of life and found that hearing aids provided hearing-impaired adults with an improvement in health-related quality of life with effect sizes varying from medium to large across multiple studies. Evidence regarding the benefits of early detection of hearing loss and intervention on the speech and language outcomes of children has grown, particularly as the prevalence of newborn hearing screening programs has increased over the last decade (Watkin et al. 2007; Kennedy et al. 2006).

Despite recent improvements in identification of hearing loss during the newborn period and implementation of early intervention processes, children with hearing loss continue to experience delays in acquisition of speech and language skills, even with the provision of early amplification. Results from two studies by Moeller and colleagues (2007a,b) highlight the differences that persist between children with hearing loss and their normal-hearing peers despite early identification and intervention. Specifically, parent-child interactions from infants with hearing loss and infants with normal hearing were video recorded every six to eight weeks from infancy until at least age three. Results indicated that even when children with hearing loss were identified and fit with amplification by 6 months of age, development of phonemes and syllable structure was significantly delayed (Moeller et al. 2007a). Delays in the transition from canonical babble to the onset of words were observed later in the same group of children (Moeller et al. 2007b). The continued presence of developmental difficulties despite timely restoration of audibility suggests that while audibility is an important prerequisite for speech and language development, a greater understanding of how audibility relates to auditory learning is necessary to maximize outcomes for children with hearing loss.

The purpose of the current research was to systematically examine the relationships between audibility and speech recognition for children. To explore how audibility may support cognitive processes necessary for the development of speech and language, the influence of audibility on working memory in children was also studied. In an effort to provide a foundation for the current state of research in this area, as well as the need for the current experiments, a review of the previous literature is necessary. First, the methods used to quantify and analyze audibility of the speech signal in clinical practice will be discussed. Extant research on audibility and auditory perception will also be highlighted, followed by a review of current theories and research regarding working memory in children. Finally, the rationale for the current research will be provided as a method of improving understanding of how audibility influences the cognitive processes required for development of speech and language.

Audibility and the Speech Intelligibility Index (SII)

Research on the relationship between speech audibility and speech understanding began 60 years ago as the result of work at Bell Telephone Labs (French & Steinberg, 1947; Fletcher & Galt, 1950). Early research was conducted primarily due to an interest in quantifying the effects of bandwidth limitations of telephone signal quality on speech understanding for normal-hearing adults. With advances in hearing-aid signal processing and improvements in the assessment of hearing sensitivity, methods to predict speech recognition for hearing impaired adults and improvements in speech recognition for hearing-aid users were developed and examined (Pavlovic et al., 1986; Humes et al., 1986; Pavlovic, 1989; Magnusson, 1996). These efforts provided the foundation for the procedures used in the current Speech Intelligibility Index (SII; ANSI S3.5-1997).

Currently, the SII is the most widely used method of quantifying loss of speech audibility due to noise and/or hearing loss in clinical audiology and hearing research. The SII is a numerical expression of the audibility of an average speech signal based on the intensity of the speech signal of interest, as well as the listener's thresholds and the level of background noise. The SII is a numerical estimate between 0 and 1 which represents the proportion of speech information that is audible to a listener. An SII value of 0 represents a speech signal that is completely inaudible to the listener, whereas an SII value of 1 represents a speech signal that is fully audible. One component of the SII calculation is the audibility coefficient, which is average level of the speech signal relative to the degree of hearing loss or noise level as a function of frequency. The other important element of the SII calculation is the band-importance function, which is characterized by numerical values that correspond to the average contribution of each frequency region to the overall speech recognition score for adult listeners. The audibility coefficient and band-importance function are multiplied together for each frequency band and then added across bands to create a single SII value. Several methods of calculating SII using a different number of frequency bands (e.g., critical-band, one-third octave band, and octave band) have been specified for different applications and stimulus characteristics (ANSI S3.5-1997).

The audibility coefficient of the SII is simply an acoustic measurement of the spectrum level of the speech signal, background noise, and listener's audiometric thresholds for each frequency band. Frequency-importance weights have typically been derived using a procedure in which the bandwidth of a speech stimulus is progressively high- and low-pass filtered to evaluate the relative contribution of each frequency region. The importance weight for each frequency band is determined by the amount of degradation in speech recognition that occurs when that band is filtered out of the stimulus (Studebaker & Sherbecoe, 1991). Using this approach, frequency-importance functions for adults have been derived for wide range of speech stimuli of varying linguistic complexity, including continuous discourse (Studebaker et al., 1987), high- and low-context sentences (Bell et al., 1992), monosyllabic words (Studebaker & Sherbecoe, 1991; Studebaker et al., 1993), and nonsense words (Duggirala et al., 1988).

Analysis of frequency-importance weights across studies for stimuli with varying amounts of linguistic and contextual cues reflect variability based on the complexity of the stimuli. For stimuli with lexical, semantic or syntactic cues such as sentences or familiar words, frequency-importance weights are reduced at higher frequencies for adult listeners. For speech stimuli with less linguistic content, such as nonsense words, listeners exhibit larger frequency-importance weights for high-frequency bands. Specifically, when linguistic and contextual information is limited, listeners require a wider bandwidth for accurate speech recognition. Relative increases in importance weights for high-frequency bands when linguistic context is reduced are likely to reflect a greater reliance on acoustic-phonetic cues of the stimulus during speech recognition. Because young children may not have the same communicative skills as adults, frequency-importance weights for children are likely to be different than those of adults, particularly at higher frequencies. However, importance weights have not been directly measured with children. Therefore, SII-based predictions of speech recognition for children are currently calculated using adult importance weights.

Following calculation of the SII, the numerical results can be applied to a transfer function in order to estimate speech recognition abilities. Prediction of speech recognition using the SII is important for estimating the communicative impact of limited audibility on infants and young children who cannot reliably participate in speech recognition assessment. Transfer functions characterize speech recognition as a function of audibility expressed as the SII for a particular corpus of speech materials (Pavlovic, 1987). For example, highly redundant speech materials, such as the Connected Speech Test (CST) have a transfer function with a steep slope and asymptote at a lower SII value, reflecting that listeners need less audibility to recognize stimuli with redundant contextual cues. Stimuli such as nonwords have transfer functions with a more gradual increase in speech recognition as a function of SII and have relatively higher asymptotes, as listeners require more spectral information in the absence of embedded linguistic cues.

Frequency-importance weights and transfer functions are two components of the SII calculation that are dynamic and variable as children develop speech and language skills. Developmental influences on two key components of the SII calculation could lead to large differences in calculations of audibility and audibility-based predictions of speech recognition for children. Despite the widespread use of the SII with children and the potential for clinically significant errors when using adult data, only Scollie (2008) has attempted to directly examine the predictions of the SII on the speech recognition scores of children. Using a test of consonant recognition to minimize differences in word knowledge between children and adults, SNR was varied from -5 to +5 dB, and SII values were calculated for each SNR. Findings from this study supported the conclusion that transfer functions derived from adults did not predict speech recognition for children adequately, regardless of hearing status. Differences in speech recognition as large as 30% between normal-hearing adults and children were observed for the same calculated SII value. The author attempted to improve predictions of speech recognition in the children in the study by using an age-related proficiency (ARP) factor that was applied to the transfer function to compensate for variability in performance across children of different ages. The application of an ARP to the transfer function significantly improved the variance accounted for in SII predictions of speech recognition in normal-hearing children, but did not result in improvements in predictions for children with hearing loss. However, the author strongly emphasized the limitations of using age alone to improve predictions of speech recognition in children, as even typically-developing children of the same chronological age have varying communicative and cognitive skills that may influence their ability to understand speech.

Bandwidth and Predictions of the SII

The relationship between the bandwidth of speech signals and auditory perception has been the focus of a large number of studies over the past decade. The benefits of providing a hearing-aid frequency response that extends beyond the current limit of 5-6 kHz have been scrutinized since Boothroyd and Medwetsky (1992) demonstrated that a limited bandwidth reduces the ability to perceive fricative phonemes such as /s/. Early investigations with adult listeners with hearing loss reported equivocal or even detrimental speech recognition outcomes for listening conditions with extended bandwidths (Byrne & Murray, 1986; Rankovic, 1991; Horwitz et al. 1991, Ching et al., 1998; Hogan and Turner, 1998; Turner and Cummings, 1999). However, subsequent findings which have considered limitations related to signal audibility (Hornsby & Ricketts, 2003; 2006) and dead regions in the cochlea (Simpson et al. 2005) have supported the conclusion that, if speech can be made audible and inner hair cell function is sufficient to encode speech in high-frequency regions, adult listeners are likely to experience improvements in speech recognition with the provision of additional high-frequency information. With a wider bandwidth, adults also report higher sound quality for both speech (Ricketts, Dittberner & Johnson, 2008) and music signals (Moore & Tan, 2003) and greater acceptable noise levels (Johnson et al. 2009) with an extended bandwidth relative to the limited bandwidth of conventional hearing aids.

Improvements in speech recognition and sound quality for wider bandwidths also have been demonstrated with both normal-hearing children, and those with hearing loss. While the perceptual advantages of an extended bandwidth are important for adult listeners, the consequences of limited auditory access for children can have significant negative consequences for communication development. For example, data from Elfenbein (1994) revealed significant delays in fricative acquisition among children with hearing loss, a finding that was reported in the previously discussed longitudinal studies of children with hearing loss (Moeller et al. 2007a). Such delays may be related to the limited bandwidth of conventional amplification. Stelmachowicz and colleagues (2001) examined the influence of bandwidth on the perception of /s/ using multiple low-pass filtering cut-offs between 2 and 9 kHz. Children with hearing loss and children with normal hearing both required a broader frequency response than adult listeners to reach maximum performance for /s/. A subsequent study (Stelmachowicz et al. 2002) of the perception of /s/ and /z/ phonemes revealed that children with hearing loss varied considerably in their ability to identify /s/ and /z/, particularly for female talkers. Although improvements in bandwidth would seem to be predicted based on the audibility of speech cues in high-frequency bands, the frequency-importance weights of the SII predict only a negligible amount of reduction in speech recognition when those bands are removed from the speech signal. For example, the SII predicts a reduction of

5% or less in speech recognition when the 8 kHz frequency band is eliminated from the stimulus.

Audibility, Auditory Working Memory and Listening effort.

Although speech recognition scores are the most frequently used metric of auditory comprehension under adverse conditions in both clinical and research settings, less attention has been paid to the effects of such conditions on working memory and other cognitive processes. The impact of limited bandwidth and audibility on long-term communication outcomes, such as language, memory and academic learning, have even more substantial implications for children's speech and language development. Auditory perception involves the listener's ability to use both acoustic-phonetic cues from the stimulus, as well as memory, attention and linguistic knowledge (see Jerger, 2007, for a review). Stimuli with more intact acoustic-phonetic representations require less cognitive effort than those with degraded cues that must be resolved using top-down processing. Normal-hearing adult listeners are often able to achieve acceptable speech recognition scores even at negative SNRs (Nilsson et al., 1994) because the speech signal contains many redundant and robust linguistic cues. Even when speech recognition accuracy may not be significantly compromised in recognition tasks, listening under adverse conditions could have negative effects on other cognitive processes important for learning. An extended bandwidth would be predicted to reduce listening effort and result in improved cognitive performance because audible acoustic cues would reduce the amount of decoding required of the listener.

In an attempt to generalize findings of previous studies to more realistic stimuli and examine the potential effects of bandwidth on auditory cognitive processing, Pittman et al. (2005) conducted a novel word-learning task with children with normal hearing and children with hearing loss. While the children with hearing loss had poorer performance on the fast-mapping task, no advantage for extended bandwidth was evident on the word learning task. In a follow-up study, Stelmachowicz and colleagues (2007) evaluated speech recognition, listening effort and novel word-learning for a bandwidth consistent with a commercial hearing aid (5 kHz) and an extended bandwidth (10 kHz). Similar to the previous study, no novel word-learning or reduction in listening effort was observed for the dual-task paradigm, despite an improvement in speech recognition for the extended bandwidth condition. Pittman (2008) hypothesized that the lack of a previously observed advantage for extended bandwidth in a novel word-learning paradigm was related to the limited number of exposures that had been used in the previous studies. Using a fast-mapping paradigm with a greater number of exposures, improved novel word-learning was observed in children with hearing loss and children with normal hearing.

Although the use of novel word-learning paradigms has strong ecological validity for predicting language acquisition, previous studies about the effects of audibility on word learning have not provided insight into the underlying cognitive mechanisms that may facilitate this process. An alternative approach would be to use dependent variables that can quantify the effect of audibility on underlying cognitive functions, such as verbal response time or item recall. The influence of noise or limited bandwidth on auditory memory skills is likely to be important for children who are dependent on acoustic cues for learning speech and language. Changes in recall and response time related to audibility have not been systematically evaluated in children, despite the potential importance for improving our understanding of underlying processes in short-term memory and cognitive processing.

While the ability to repeat an auditory stimulus accurately is important, how reliably the stimulus is committed to memory is critical for word learning and comprehension. Recall refers to the ability to recollect a group of stimuli. The consequences of background noise on listening effort and memory have been studied for over four decades. For example, Rabbitt (1968) demonstrated that the presence of random noise negatively affected the recall of digits by young adults with normal hearing, even when the level of the noise was not high enough to alter the accuracy of digit recognition. Surprenant (1999) reported similar decrements in an auditory serial recall task in competing noise when identification was the same as in quiet for consonant-vowel (CV) stimuli. Several investigators have examined differences in recall between young adults and older adults as a method of characterizing changes in auditory memory related to the aging process. Pichora-Fuller and colleagues (1995) used high- and low-predictability sentences to compare recall between a group of young adults and older adults. While both older and younger adults recalled fewer words as SNR became poorer, older adults had poorer recall than young adults even when attempts were made to equate identification between age groups. Surprenant (2007) compared serial recall of listeners across the age range of 30 to 80 years-old using nonwords. Similar to previous studies, recall became poorer as SNR deteriorated with a trend of decreasing performance as subjects increased in age. These results suggest that the presence of noise affects the process of committing an auditory stimulus to short-term memory even in young adults with normal hearing. It is likely, therefore, that children may have even greater difficulty with recall or other short-term memory tasks in the presence of noise.

Studies of the development of recall and working memory in children have been carried out to examine the role of working memory in language development. These studies may provide direct insight into the underlying mechanism for the bandwidth advantage observed in Pittman's (2008) novel word-learning research. Data on short-term memory in children indicate that recall improves as a function of age between 7 years and 11 years in typically-developing children (McCormack et al., 2000). However, age is not the only factor that can influence performance on recall tasks with children. Studies have also found that children with smaller vocabularies exhibit deficits in nonsense word recall compared to peers with larger vocabularies, highlighting the importance of lexical knowledge in recall paradigms (Edwards et al. 2004). Children with hearing loss also exhibit poorer recall compared to age-matched children with normal hearing (Jutras, 2006), although the influences of limited audibility and language deficits associated with hearing loss are difficult to separate as potential contributors to poorer recall in hearing-impaired subjects.

The relationship between working memory and word learning has been supported by the work of Gathercole (2006). Based on the early theory of working memory proposed by Baddeley & Hitch (1974), Gathercole suggests that auditory working memory, known as the phonological loop, is an essential component in the process of analyzing acoustic-phonetic representations of the stimulus and integrating them into existing phonological representations. Previous word-learning studies with have found an advantage on word-learning tasks for novel targets with higher relative frequency of occurrence of phoneme sequences, or phonotactic probability. Advantages for stimuli with higher phonotactic probabilities have been demonstrated in studies of working memory in children (Gathercole et al. 1999), which the authors propose is related to the existing phonological representations that are more likely to exist for higher phonotactic probability sequences.

However, subseqeuent studies of word learning in children (Storkel, 2003) and adults (Storkel, Armbrüster & Hogan, 2006) present a more complex model of word learning where both phonotactic probability and lexical neighborhood density, which refers to the number of words that sound similar to a target word, may both contribute to the process of word-learning. Specifically, phonotactic probability may influence learning of new words for which there is not an existing lexical representation, while lexical neighborhood density may influence the integration of new words into the mental lexicon. In summary, perception of phonetic sequences in nonwords during speech recognition may interact with higher-level cognitive processes and lexical knowledge. Gupta (2005) proposed that nonword recognition is a recall task with individual phonemes as items in a sequence. When the phoneme sequences of nonwords are analyzed, the response patterns show similar patterns of primacy and recency as do working memory tasks with sequences of words as targets. The processing of nonwords by children has been used to provide a measure of phonemic sequencing and working memory in children (Archibald & Gathercole, 2006).

Another frequently utilized metric of listening effort is reaction time. Reaction time can be generally described as the amount of time taken to complete a task. Reaction time can be measured for a single task, as in the case of measuring the time between stimulus onset and onset of a verbal response from the listener in a word recognition task (Vitevitch & Luce, 2005) or from a secondary task, such as a button push prior to a verbal response by the subject (Conlin et al., 2005; Wong et al., 2008). Reaction time varies based on complexity of the task, sensory modality, and individual characteristics such as age, level of arousal, and attention (Luce, 1986). Although reaction time has been used frequently in experimental psychology as an index of cognitive processing time (Whelan, 2008), few studies have used reaction time as an index of listening effort across tasks of varying difficulty for the same group of listeners. Wong and colleagues (2008) measured reaction time during a word recognition task in noise as part of an analysis of patterns of brain activation during functional magnetic resonance imagining (fMRI). Participants pressed a button corresponding to the location of a target word in one of three boxes displayed visually on a monitor. Reaction time was calculated based on the time required for the subject to press the button. Results revealed that response time increased as SNR decreased, consistent with greater listening effort at lower SNRs. Another investigation by Conlin and colleagues (2005) used reaction time to compare short-term memory across three tasks with varying demands on short-term memory. In this context, reaction time appeared to be sensitive to differences in short-term memory skills between 7 and 9 year-old children across different tasks. Hicks and Tharpe (2002) also measured reaction time in a dual-task paradigm to compare listening effort between age-matched groups of normal hearing and hearing-impaired children. Both groups were required to push a button in response to a random signal from a light-emitting diode (LED) before repeating monosyllabic words at three SNRs. Children with hearing loss exhibited longer response times as well as poorer speech recognition scores when compared to the group of normal-hearing children.

One of the limitations of measuring reaction time using a dual-task paradigm is that a multiple task may be more difficult for younger children. A study of listening effort using a dual-task paradigm by Choi et al. (2008) revealed that when listening conditions became challenging, young children would often only perform one of the tasks. An alternative that has been used previously is to measure reaction time using verbal response time, which is the time from the onset of the stimulus to the onset of a listener's verbal response during a speech recognition task. Vitevitch and Luce (2005) utilized this method of measurement in their study of the influence of phonotactic probability on nonsense word identification. Results indicated that there was no difference in verbal response time between nonsense word stimuli with high and low phonotactic probabilities for a group of young adults. Verbal response time would be expected to increase as listening conditions become more difficult.

Statement of the problem

The SII is widely used to estimate audibility and speech recognition for children, despite the fact that the only previous study (Scollie, 2008) conducted on the SII with children suggested that the SII over-predicts speech understanding in children. Two components of the SII calculation are likely to contribute to inaccurate predictions of audibility and speech recognition for children: frequency-importance weights and the transfer functions that characterize speech recognition as a function of the SII. Because children are developing speech and language skills, younger children may be more dependent on the acoustic and phonetic information in the stimulus than older children and adults. Therefore, the goal of the first study was to derive frequency-importance functions for children and adults, as well as the transfer functions for a large group of normal-hearing children, in order to help improve audibility-based predictions of speech recognition for children. Frequency-importance functions were expected to vary as a function of age, reflecting a greater reliance by children on the acoustic-phonetic aspects of speech recognition due to their relative inability to rely on cognitive and linguistic support.

The goal of the second study was to better describe the relationship between audibility and working memory in children, in order to account for previously observed patterns of novel word-learning for children when an extended stimulus bandwidth was used. Two different tasks of auditory working memory were conducted using nonwords in one task and real words in the other to evaluate if the lexicality of the stimulus helped to mitigate the negative effects of noise and limited bandwidth on speech recognition and item recall.

Chapter 2 - Estimation of speech recognition in children using the speech intelligibility index (SII)

Introduction

The primary goal of providing amplification for children with permanent hearing loss is to restore audibility of the speech signal to facilitate development of communication (Bagatto et al. 2010; Seewald et al. 2005). Quantification of the audibility of the speech signal during clinical hearing-aid fitting and verification is therefore essential to ensuring that children have access to the acoustic cues that comprise speech. Because infants and young children are often unable to participate in speech recognition testing or other methods of behavioral hearing-aid validation, clinicians must rely on objective estimates of audibility derived from acoustic measurements of the hearing-aid output and estimate the outcome based on previous studies of the relationship between audibility and speech understanding with adult listeners. The purpose of the current study is to evaluate the consequences of these assumptions based on differences in speech recognition between children and adults. An additional goal of the present study is to specify the impact that these differences may have on clinical estimates of speech recognition based on audibility.

One widely-used method of estimating the effects of stationary noise and/or hearing loss on the audibility of the speech signal is the Speech Intelligibility Index (SII; ANSI, 1997). The SII specifies the weighted audibility of speech across multiple frequency bands in order to estimate the proportion of the signal that is audible to a listener. Calculation of the SII requires the hearing thresholds of the listener and the spectrum level of both the background noise and speech signals. For each frequency band in the calculation, a frequency-importance weight is applied to estimate the contribution of that band to the overall speech recognition score. Additionally, the audibility of the signal is determined by the level of the speech spectrum compared to either the listener's threshold or noise spectrum in each band, whichever is greater. The SII is calculated as:

where *n* represents the number of frequency bands included in the summation. I_i and A_i represent the importance and audibility coefficients for each frequency band, which are multiplied and summed to produce a single value between 0 and 1. An SII of 0 indicates that none of the speech signal is audible to the listener, whereas an SII of 1 represents a speech signal that is fully audible.

In addition to providing a numerical estimate of speech audibility, SII calculations can also be applied to transfer functions to estimate the expected proportion of speech understanding that a listener is likely to achieve with a given amount of audibility. Transfer functions based on adult listeners with normal hearing have been empirically derived for a wide range of speech stimuli from nonword syllables to sentences. These sigmoidal functions have steeper slopes and asymptote at lower SII values when lexical, semantic or syntactic cues are available to listener, reflecting the listener's use of linguistic and contextual information when the audibility of acoustic cues is limited (Pavlovic, 1987). The ability to use transfer functions to predict speech recognition on the basis of audibility has specific utility for young children who may be unable to participate in speech recognition testing due to their age and/or speech and language concerns.

The accuracy of speech recognition predictions based on the SII for adult listeners has been evaluated in multiple studies over the last 65 years. Foundational research at Bell Telephone Labs attempted to estimate speech understanding based on the amount of spectral content available to the listener for the purposes of telecommunication systems (French & Steinburg, 1947; Fletcher & Galt, 1950). Further research by Kryter (1962a; 1962b) led to the development of the first ANSI standard for the Articulation Index (AI; ANSI S3.5-1969). Since that time, the AI has been proposed for a wide range of clinical applications including predicting improvement in speech understanding in stationary noise with amplification (Rankovic, 1991) and the effects of hearing loss on speech understanding (Pavlovic 1991). The most recent standard (ANSI S3.5-1997) changed the name of the calculation procedure from AI to Speech Intelligibility Index (SII). Results from the current SII procedure have been applied to set gain prescriptions for prescriptive fitting formulae for hearing aids (Seewald et al. 2005; Byrne et al. 2001) and have been adapted to evaluate the effects of hearing-aid signal processing strategies on the speech signal (Kates & Aerhart, 2005). While SII predictions of speech understanding for adults with hearing loss are less accurate for individuals with greater degrees of hearing loss (Ching et al. 1998) or for precipitously sloping hearing loss configurations (Dubno et al. 1989), modifications to the SII to account for distortion related to hearing loss and general factors with the talker and listener have resulted in some improvement of such predictions for adult listeners (Ching et al. 2001; Humes 2002).

Despite the potential utility of the SII for estimating audibility and predicting speech recognition in children, research regarding the accuracy of SII predictions for children has been more limited. Stelmachowicz and colleagues (2000) used sentences with varying semantic content to measure speech understanding in noise for groups of children with normal hearing, children with hearing loss and adults with normal hearing. Results indicated that in order to reach levels of speech recognition similar to adults, both groups of children required greater audibility as measured by the SII. Other studies have evaluated the relationship between audibility and speech understanding in children to determine the stimulus characteristics that may predict the need for greater stimulus audibility in children than in adults. Broader stimulus bandwidths (Mlot et al, 2010; Stelmachowicz et al. 2001) and higher stimulus sensation levels (Kortekaas & Stelmachowicz, 2000) have both been found to help maximize speech recognition in children. Gustafson and Pittman (2010) attempted to further describe the relationship between audibility and speech understanding in children and adults by varying the sensation level and stimulus bandwidth of meaningful and nonsense sentences to create conditions with equivalent SII values, but differing bandwidth. The main hypothesis was that equivalent SII values across conditions would result in similar speech recognition in adults and children. However, their results demonstrated that for conditions with equivalent SII, speech recognition performance was better in conditions with a lower sensation level and a broader bandwidth than in conditions where the spectral information was limited, but presented at a higher sensation level. These results demonstrate that the loss of spectral cues cannot necessarily be compensated for by increasing sensation level, and that listening conditions with equivalent SII may not necessarily result in the same level of speech recognition.

The importance of estimating speech recognition for children under listening conditions with limited bandwidth has recently been highlighted in studies examining speech and language outcomes for children with hearing loss. In a longitudinal study, Moeller and colleagues (2007a) evaluated the progression and phonemic characteristics of canonical babble among children with normal hearing and hearing loss. Their results suggested that while children with hearing loss acquired most classes of consonants in a delayed, but parallel, time frame to age-matched, normal hearing peers, the acquisition of the fricative and affricate classes of consonants did not progress in the same manner. The authors concluded that the delay for the fricatives and affricates could be related to the limited high-frequency bandwidth provided by conventional hearing aids.

Despite the use of the SII in quantifying audibility for children in clinical applications, few studies have formally evaluated age-dependent variability in SII predictions of speech recognition. Scollie (2008) evaluated the relationship between SII and speech recognition for normal-hearing adults and children and children with hearing loss. Using nonsense disyllables, speech recognition was measured under conditions with varying audibility, including in quiet and in speech-shaped noise at four different signal-to-noise ratios (SNRs). Both groups of children had poorer speech recognition than adults for the same SII. In some cases, differences of 30% or greater were observed at the same SII, both within groups of children and between children and adults. These findings demonstrate that the current SII is likely to overestimate speech understanding for children and does not reflect the variability of children's speech recognition skills. The limitations of the SII to predict speech recognition in children has significant implications for the clinical utility of these measures. Specifically, estimates of the impact of hearing loss on speech understanding and the benefits provided by amplification that are based on the SII could result in poorer speech recognition outcomes for children than would be predicted.

Differences between the auditory skills of adults and children are likely to affect the SII estimates of audibility and speech understanding. Two potential aspects of the SII calculation that may vary as a function of age and development are the transfer functions used to predict speech recognition and the frequency-importance weights used to calculate the SII. Transfer functions that relate SII audibility estimates to speech recognition scores have primarily been developed using adult listeners. Numerous studies have demonstrated that speech recognition performance differs between adults and children under adverse conditions such as background noise and reverberation (Elliot, 1979; Nabalek & Robinson 1982; Johnson, 2000; Neuman et al. 2010). Performance-intensity functions obtained with children suggest that children's performance is more variable and requires a higher SNR to reach maximum performance than adults on the same task (McCreery et al 2010). While audibility of the speech signal is necessary for speech understanding in children, the SII alone does not appear to be sufficient to predict the range and variability in speech recognition outcomes in children. Speech recognition requires listeners to use the audible acoustic cues in the speech signal, as well as their linguistic knowledge. Particularly for children who vary in their mastery of linguistic cues to support speech recognition, knowing the degree to which speech is audible is only one of the factors that could influence predictions of speech recognition.

The frequency-importance weights in the SII calculation are another aspect that may result in differences in audibility-based speech recognition predictions between adults and children. Frequency-importance functions are frequency-importance weights derived at each frequency band for a specific stimulus. These functions have been derived with adult listeners for a wide range of speech stimuli of varying complexity, including continuous discourse (Studebaker et al., 1987), high- and low-context sentences (Bell et al., 1992), monosyllabic word lists used for audiological testing such as CID W-22 (Studebaker & Sherbecoe, 1991), NU-6 (Studebaker et al., 1993), and nonsense words (Duggirala et al., 1988). Collectively, these studies reveal that for stimuli with redundant lexical or syntactic cues such as familiar words or sentences, importance weights for adult listeners are reduced at higher frequencies. For speech stimuli with more limited linguistic content, such as nonsense words, adult listeners exhibit larger importance weights for high-frequency bands. This pattern suggests that when linguistic and contextual information is limited, listeners require more spectral information in the high frequencies for accurate speech recognition. Because children may not have the same level of linguistic knowledge as adults, frequency-importance weights for children may be different than those of adults, particularly in the high frequencies. Importance functions have not previously been obtained with children. As previously discussed, children require a wider bandwidth to achieve the same level of speech understanding as adults. Studies have also shown that children experience greater degradation in speech understanding when high-frequency spectral cues are limited (Eisenberg et al. 2000). These differences in how children use high-frequency spectral cues to facilitate speech recognition may alter frequency-importance weights for young listeners. However, because importance weights have not been derived for the pediatric population, SII-based audibility and related predictions of speech recognition for children are currently calculated using adult weights.

Multiple challenges related to the methods used in the measurement of frequency-importance functions are likely to have limited previous attempts to obtain these data with children. Frequency-importance weights are typically derived using a speech recognition task in which the speech signal is progressively high- and low-pass filtered to systematically evaluate the relative contribution of each frequency region to the overall speech recognition score. The importance weight for each band is determined by the average amount of degradation in speech recognition that occurs when a given band is removed from the stimulus for a large group of listeners (Studebaker & Sherbecoe, 1991). The number of frequency bands for which frequency-importance weights have been obtained in studies with adults varies from a minimum of six bands for the octave-band calculation procedure to twenty-one bands for the critical-band method. Greater accuracy is achieved for procedures that use a larger number of bands, particularly for stimuli where the spectrum level of speech or noise varies within an octave band (ANSI 1997). Additionally, speech recognition is measured at multiple SNRs for each frequency band condition to estimate the contribution of a specific band over a wide range of audibility. As a result, studies of adult frequency-importance functions often have more than 60 listening conditions due to the combinations of bandwidth and SNR conditions that must be assessed. Even if the task were adapted to limit the number of conditions to avoid age-related confounds such as attention and fatigue, the minimum number of listening conditions that would be required if four SNRs are used for an octave band method would be approximately twenty-eight once a full bandwidth condition is included.

The linguistic complexity of the stimuli used to obtain frequency-importance weights with children is also an important experimental consideration that could significantly influence the importance values obtained from the task. Because importance weights derived from adult listeners show varying levels of importance based on the availability of lexical, semantic, syntactic and other linguistic cues available in the stimuli, the listener's knowledge and ability to use these cues can influence the frequency-importance function for different types of speech stimuli. Although not specifically examined in previous studies of importance functions with adults, the probability of occurrence of combinations of phonemes, or phonotactic probability, of the stimuli has been shown to influence the ability of children to identify nonword speech tokens (Munson, Kurtz & Windsor, 2005; Edwards, Beckman & Munson 2004). While previous studies have demonstrated that children as young as four years of age are able to use linguistic cues to support speech recognition under adverse conditions (Nittrouer & Boothroyd, 1990), children are likely to vary in their ability to use these cues. Variability in speech recognition ability for children, even within the same age group, presents challenges in the development of accurate frequency-importance functions for this population.

The goal of the present study was to evaluate age-related changes in the relationship between the SII and speech recognition. Younger children were expected to perform more poorly than older children and adults for the same SII. To further our understanding of the underlying mechanisms for these differences, age- and frequency-dependent differences in speech recognition were evaluated by deriving frequency-importance functions from children and adults with normal hearing. A modified filtered speech recognition paradigm that has been used in previous frequency-importance studies with adults (Studebaker & Sherbecoe, 1991, 2002; Bell, Dirks & Trinel, 1992) was used to test three primary hypotheses in children between five and twelve years of age and a group of young adults. First, speech recognition for younger children was expected to be poorer and more variable than for adults and older children when compared across listening conditions with the same SII. Second, the amount of degradation in speech recognition when high frequency bands are removed from the signal is likely to be age-dependent, reflecting a greater reliance on spectral cues for speech recognition in noise for younger listeners. Individual phoneme scores were obtained to determine if differences in perception for specific phonemes could account for age-related changes in speech recognition. Finally, adult-child differences in frequency-importance functions were predicted to decrease as a function of age. This hypothesis is based on observations in previously cited studies regarding spectral cues and bandwidth in children, as well as studies that have demonstrated that children's speech recognition in noise improves as a function of age until approximately age 12, when performance is similar to adults (Elliiot, 1979; Hnath-Chisolm et al. 1999; McCreery et al. 2010).

Method

Participants

One-hundred and thirty seven individuals participated in the current study. One hundred and sixteen children between 5 years, 3 months and 12 years, 11 months [mean = 9.16 years, standard deviation (SD) = 2.13 years] and nineteen adults between 20 and 48 years [mean = 29.9 years, SD = 8.53 years] were recruited from the Human Research Subjects Core database at Boys Town National Research Hospital. Participants were paid $12 per hour for their participation, and children also received a book. All listeners had clinically normal hearing in the test ear (15 dB HL or less) as measured by pure-tone audiometry at octave frequencies from 250 Hz – 8000 Hz. One child and one adult did not meet the audiological criteria for the study and were excluded from participation. None of the participants or their parents reported any history of speech, language or learning problems. Children were screened for articulation problems that could influence verbal responses using the Bankson Bernthal Quick Screen of Phonology (BBQSP; Bankson & Bernthal, 1990). The BBQSP is a clinical screening test that uses pictures of objects to elicit productions of words containing target phonemes. One child did not pass the age-related screening criterion and did not participate in the study. Receptive language skills were measured for each participant using the Expressive Vocabulary Test, Form B (EVT; Williams, 2007). All of the children in the study were within two SD of the normal range for their age [Mean = 105; Range = 80 – 121].

Materials

Stimuli

Speech recognition was assessed using consonant-vowel-consonant (CVC) nonword stimuli that were developed for this study. The stimuli were created by taking all possible combinations of CVC using the consonants /b, ʧ, d, f, g, h, ʤ, k, m, n, p, s, ʃ, t, θ, ð, v, z, ʒ/ and the vowels / a, i, I, ɛ, u, ʊ, ʌ/. The resulting CVC combinations were entered into an online database based on the Child Mental Lexicon (CML; Storkel

& Hoover, 2010) to identify all of the CVC stimuli that were real words likely to be within a child's lexicon and to calculate the phonotactic probability of each nonword using the biphone sum of the CV and VC segments. All of the real words and all of the nonwords that contained any biphone combination that was illegal in English (biphone sum phonotactic probability = 0) were removed from the stimulus set. Additional review of the remaining CVCs was completed to remove slang words and proper nouns that were not identified by the online calculator. After removing all real words and phonotactically illegal combinations, 1575 nonword CVC stimuli remained. In order to create a set of stimuli with a limited range of phonotactic probabilities, the mean and SD of the biphone sum for the entire set was calculated. Phonotactic probability has been demonstrated to impact the recognition of nonword stimuli by adults (Vitevitch & Luce, 2005) and children (Edwards, Beckman & Munson, 2004; Gathercole et al. 1999). In order to limit the influence of phonotactic probability on the task, the 735 CVC nonwords with phonotactic probability within +/ - 0.5 SD from the mean were elected for recording. Stimuli were recorded for two female talkers at rate of 44.1 kHz. Three exemplars of each CVC nonword were recorded. Consensus scoring was used to identify the best production of each stimulus. Specifically, two raters independently and blindly selected the best production on the basis of clarity and vocal effort. In thirty-seven cases where the two independent raters did not agree, a third rater listened to the nonwords and selected the best production using the same criteria. To ensure that the stimuli were intelligible, speech recognition testing was completed with three adults with normal hearing. Stimuli were presented monaurally at 60 dB SPL under Sennheiser HD-25-1 headphones.

Any CVC nonword that was not accurately repeated by all three listeners was excluded from the stimulus set. Finally, the remaining words (725) were separated into 25-item lists that were balanced for occurrence of initial and final consonant (See Appendix B for the lists of stimuli and phonotactic probabilities). Filtering of the stimulus set was completed using MATLAB to create stimuli with high- and low-pass filtering characteristics that correspond with

Table 1. Filter conditions.

Condition	**Frequency bands**
Full band (FB)	250 – 8000 Hz
High-pass (HP)	
HP1	500 – 8000 Hz
HP2	1000 – 8000 Hz
HP3	2000 – 8000 Hz
Low-pass (LP)	
LP1	250 – 4000 Hz
LP2	250 – 2000 Hz
LP3	250 – 1000 Hz

the center frequencies specified by the octave-band method for the SII (ANSI, 1997). Table 1 displays the filter bandwidths for each condition.

Filtering was completed using a series of infinite-impulse response (IIR) Butterworth filters, as in previous studies (Studebaker & Sherbecoe, 2002). The stimuli were filtered to create a full bandwidth condition that contained all six octave bands. Removing each octave band successively through filtering resulted in three high-pass and three low-pass conditions. All stimuli were processed under all seven filter conditions. Steady-state speech-shaped noises were created to match each talker's long-term average speech spectrum (LTASS). Figure 1 shows the LTASS for each talker compared to the LTASS used in the ANSI standard for SII calculation. The spectrum of the ANSI standard is based on a male talker, whereas the two talkers for the current study were both female.

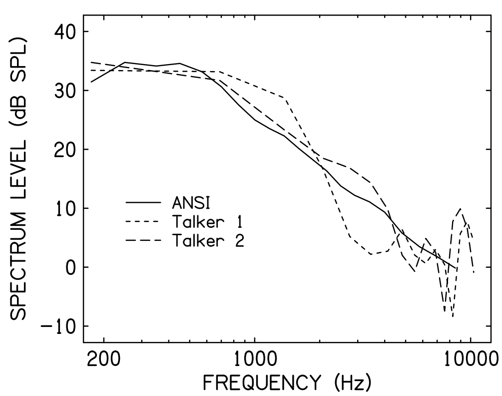

Figure 1 – Average speech spectrum as a function of frequency with ANSI standard for SII (solid line-S3.5-1997), Talker 1 (small dashed line) and Talker 2 (large dashed line).

The steady-state masking noise was created in MATLAB by taking a Fast Fourier Transform (FFT) of a concatenated sound file containing all of the stimuli produced for each talker, randomizing the phase of the signal at each sample point, and then taking the inverse FFT. This process preserves the long-term average spectrum, but eliminates temporal and spectral dips.

Instrumentation

Stimulus presentation, including control of the levels of speech and noise files during the experiment, and response recording was performed using custom software on a personal computer with a Lynx Two-B sound card. Sennheiser HD-25-1 headphones were used for stimulus presentation. A Shure head-worn boom microphone was used to record subject responses for later scoring. Pictures were presented via a computer monitor during the listening task to maintain subject interest during the listening task. The sound level of the speech and noise were calibrated using a Larson Davis (LD) System 824 sound level meter with a LD AEC 101 IEC 318 headphone coupler. Prior to each subject, the sound level was verified by playing a pure tone signal through a voltmeter and comparing the voltage to that obtained during the calibration process for the same pure tone.

SII Calculations

For each combination and filter condition, the SII was calculated. The octave-band method was used with frequency-importance weighting function for nonsense syllables and a non-reverberant environment. The octave band spectrum levels of the speech and noise stimuli were measured using the same apparatus used for calibration. The levels of speech and noise were converted to free-field using the eardrum to free-field transfer function from the SII. The octave band spectrum levels of speech and noise for each condition were used to calculate the SII for each condition. The calculated SII for each combination of filter and SNR are listed in Table 2.

Table 2 – SII calculations for each condition

	SNR				
Bandwidth	**0 dB**	**3 dB**	**6 dB**	**9 dB**	**Quiet**
FB	0.4101	0.4922	0.5744	0.6566	0.9942
LP1	0.3903	0.4684	0.5467	0.6249	0.8784
LP2	0.2940	0.3581	0.4098	0.4678	
LP3	0.1586	0.1915	0.2245	0.2575	
HP1	0.3897	0.4661	0.5443	0.6226	
HP2	0.3409	0.4072	0.4736	0.5400	
HP3	0.2515	0.3007	0.3499	0.3991	

Procedure

Participants and the parents of children who participated took part in a consent/assent process as approved by the Institutional Review Boards of Boys Town National Research Hospital and The University of Nebraska-Lincoln. All of the procedures were completed in a sound-treated room. Pure tone audiometric testing was completed using TDH-49 earphones. The children completed the BBQSP and EVT. Participants were seated at a table in front of the computer monitor and instructed that they would hear lists of words that were not real words and to repeat exactly what they heard. Participants were encouraged to guess if they were not sure what they heard. Each subject completed a practice trial in the full bandwidth condition at the most favorable SNR (+ 9 dB) to ensure that the subject understood the task and directions. Full bandwidth and LP1 conditions were then completed in quiet to provide two optimal conditions for comparison.

Following completion of the practice trial and two quiet conditions, the filtered speech recognition task was completed in noise using one 25-item list per condition. List number, talker, filter condition and SNR were randomized using a random sequence generator. The presentation order of the stimuli within each list was also randomized. Although feedback was not provided on a trial-by-trial basis, children were encouraged regardless of their performance after each list. Based on pilot testing and results from previous studies with children (McCreery et al. 2010), four SNRs were used to obtain performance-intensity functions (0, +3, +6, + 9). These levels were also chosen to provide a range of varying SII values. To limit the length of the listening task and minimize the likelihood of changes in performance related to fatigue and decreased attention, each participant listened to two of four possible SNRs for each filter condition. For example, each participant would listen to either the +9/+3 dB SNRs or the +6/0 dB SNRs for each filter condition. Subsequent listeners within same age group (Children: 5-6 years, 7-8 years, 9-10 years, 11-12 years, and Adults) completed the other SNRs for each filter condition. In all, each participant listened to two SNR conditions for each filter setting (7) for a total of 14 conditions. Participants were given one or two short breaks during the task depending on their age. The entire task typically took 90 minutes for children and 60 minutes for adults.

Scoring of each nonword as correct or incorrect was completed online during the listening task. After the session, recordings of each participant were reviewed and scored to cross-check online scoring, as well as to analyze the phonemes in each response as correct or incorrect. Phonemes were judged to correspond to one of the phonemes in the stimulus set or were placed in a category for responses that were either unintelligible or not in the phonemes used to construct the nonwords for the current investigation. Confusion matrices were created for each subject and listening condition to allow for an analysis of specific errors that may have contributed to differences in nonword recognition.

Results

Nonword recogntiion

Prior to statistical analysis, proportion correct nonword recognition scores were converted to Rationalized Arcsine Units (RAU; Studebaker, 1985) to normalize variance across conditions. Because each child only listened to half of the SNR conditions for each filter condition, nonword recognition results represent combined results between two children within the same age group. Nonword recognition in the 250 Hz –1000 Hz low-pass condition were consistently near 0% correct for all subjects and were excluded from subsequent analyses of variance due to this lack of variance. To evaluate changes in nonword recognition as a function of age, a factorial repeated-measures analysis of variance (ANOVA) was completed with stimulus bandwidth and SNR as within-subjects factors and age-group (Children: 5-6 years, 7-8 years, 9-10 years, 11-12 years, and Adults) as a between-subjects factor. The main effect of age group was significant, $F(4,61) = 17.687$, $p < 0.001$, $\eta^2_p = 0.537$, indicating that nonword recognition scores were significantly different across age groups. To evaluate the pattern of significant differences while controlling for Type I error rate, post hoc comparisons were completed using Tukey's Honestly Significant Difference with a calculated minimum mean significant difference of 7.1 RAU. Adults had significantly higher performance than all four age groups of children. The mean differences between 5-6 year-olds and 7-8 year-olds (6.14 RAU) and between the 9-10 year-olds and 11-12 year-olds (0.41 RAU) were not significant. However, the 9-10 year-olds and 11-12 year-olds had significantly higher nonword recognition than the two younger groups of children. Based on this pattern and the lack of significant higher-order interactions involving age group, data for children is plotted by two age groups: younger children, which included children ages 5 years: 0 months to 8 years: 11 months ($n = 52$) and older children, which included children ages 9 years: 0 months to 12 years: 11 months ($n = 62$). Adults are plotted as a separate age-group (n = 18). Mean scores for each age group are shown for each condition in Figures 2 and 3.

The main effect for stimulus bandwidth, $F(5,57) = 354.709$, $p < 0.001$, $\eta^2_p = 0.969$, was significant. Post hoc testing using Tukey's HSD with a calculated minimum mean difference of 9.6 RAU, revealed the highest nonword recognition scores in the full bandwidth conditions, and significant degradation in nonword recognition scores for each subsequent high- and low-pass filtering condition. The main effect of SNR was also significant, $F(5,57) = 354.709$, $p < 0.001$, $\eta^2_p = 0.969$, with the expected pattern

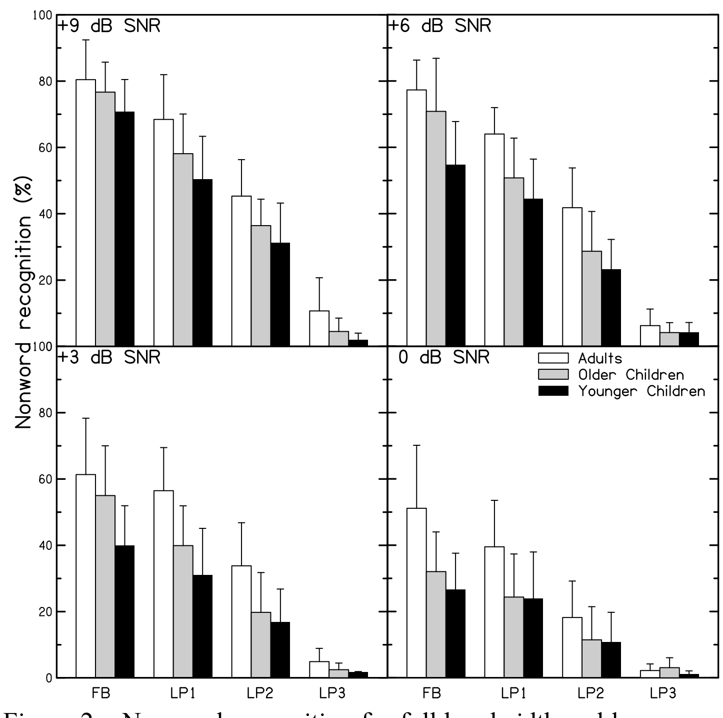

Figure 2 – Nonword recognition for full bandwidth and low-pass condition for adults (white), older children (gray) and younger children (black). Error bars are standard deviations. Each panel is SNR.

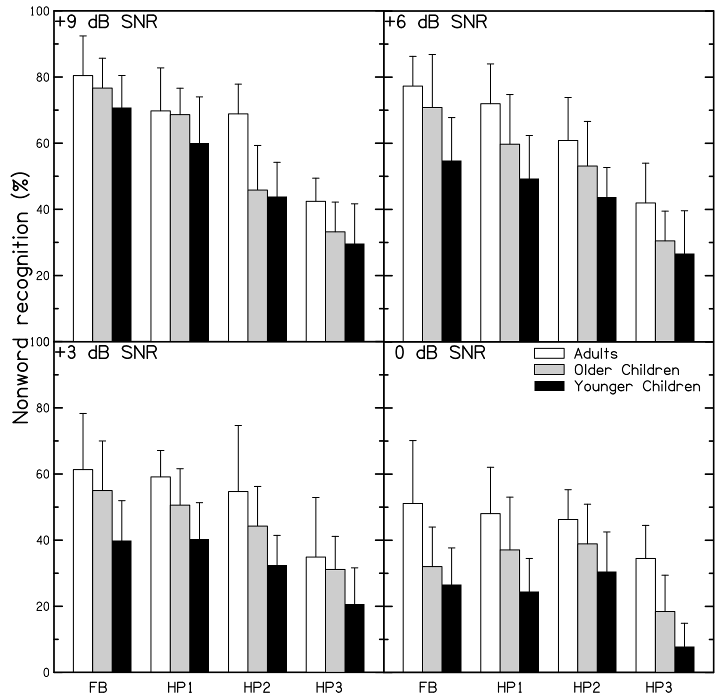

Figure 3- Nonword recognition for full bandwidth and high-pass conditions for adults (white), older children (gray) and younger children (black). Error bars are standard deviations. Each panel is SNR.

of decreasing nonword recognition as SNR decreased with significant differences between all four SNR conditions on post hoc tests based on Tukey's HSD with a calculated minimum mean difference of 4.8 RAU. The two-way interaction between stimulus bandwidth and SNR was significant, $F(15,915) = 8.804$, $p < 0.001$, $\eta^2_p = 0.126$, suggesting that the pattern of decreasing speech recognition for SNR was different across conditions of stimulus bandwidth. As anticipated, degradation in performance with decreasing SNR was greater when the bandwidth of the stimulus was increasingly limited; however, this pattern was not observed for all bandwidth conditions. In general, decreases in nonword recognition for the same SNR were greater for low-pass listening conditions than for high-pass listening conditions. Post hoc tests using Tukey's HSD with a calculated minimum mean significant difference of 8.6 RAU revealed different patterns of results for full bandwidth, high-pass, and low-pass conditions. For the full bandwidth condition, significant changes in nonword recognition were observed across all four SNRs. For the low-pass conditions, a similar pattern of significant differences was observed across all four SNRs until nonword recognition reached floor levels of performance. For high-pass conditions, performance differences between +6 and +9 dB SNR were not significant, but significant differences were observed between the +6, +3 and 0 dB SNR conditions. EVT standard score was significantly correlated with mean nonword recognition score ($r = 0.25$, $p < 0.001$).

Frequency-importance weights

Nonword recognition scores were used to derive frequency-importance weights for octave band frequencies for the adults, older children and younger children. To obtain the importance of each octave band to the nonword recognition score, the mean proportion of nonwords correct was calculated for each condition of stimulus bandwidth by averaging across the four SNRs for that condition. The importance of each octave band was the amount of degradation in nonword recognition that was observed when that octave band was excluded. For example, the 8000 Hz importance weight was calculated as the mean difference between the full bandwidth condition for each subject and the low-pass condition without 8000 Hz. Derived frequency-importance functions are plotted in Figure 4 with the nonword importance function from the current ANSI standard.

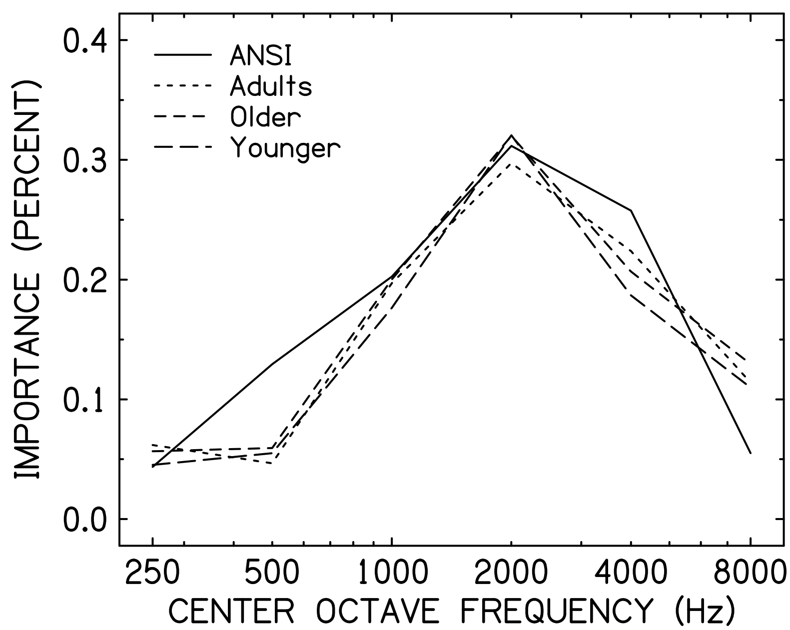

Figure 4-Frequency-importance weight as a function of octave frequency band for the ANSI standard for SII for nonword syllables and for the current study groups (Adults – small dashed line; Older children – medium dashed line; Younger children – large dashed line).

An analysis of variance with frequency-importance weight as a within-subjects factor and age-group as a between subjects factor revealed no significant differences across the three age groups, $F(10,315) = 1.088$, $p = 0.371$, $\eta^2_p = 0.033$.

Transfer Functions

The purpose of derived transfer functions is to allow estimation of speech recognition from the SII. In the current study, the transfer function for each age group was also calculated to examine the accuracy of SII predictions of speech recognition as a function of age. The transfer functions were derived as in previous studies (Scollie 2008; Studebaker & Sherbecoe, 1991, 2002) using the equation:

$$S = (1\text{-}10^{-SII/Q})^{N}$$

where S is the proportion correct speech recognition score, SII is the calculated SII for each condition and Q and N are fitting constants that define the slope and curvature of the transfer function. A nonlinear regression with SII as a predictor and nonword recognition as the outcome converged in twelve iterations revealed that the SII accounted for 78% of the variance in adult nonword recognition scores with an RMS error of 4.1 RAU. The transfer functions for the older and younger children were fit using the same nonlinear regression approach. For the older group of children, the solution converged in five iterations and accounted for 67.6% of the variance in nonword recognition with an RMS error of 11.1 RAU, whereas for the younger group the solution converged in six iterations and accounted for 65.9% of the variance in nonword recognition with an RMS error of 8.2 RAU. Regression coefficients for all three age groups are displayed in Table 3. The transfer functions for the adults, and the older and younger children are shown in Figure 5.

Table 3 – Parameter estimates for transfer functions

Age Group	Parameter	Estimate	Std. Error	95% Confidence Interval Lower	95% Confidence Interval Upper
Adults	Q	.352	.013	.326	.377
	N	-1.830	.036	-1.900	-1.760
Older	Q	.450	.011	.428	.471
	N	-1.918	.019	-1.956	-1.881
Younger	Q	.570	.015	.539	.600
	N	-1.987	.019	-2.022	-1.953

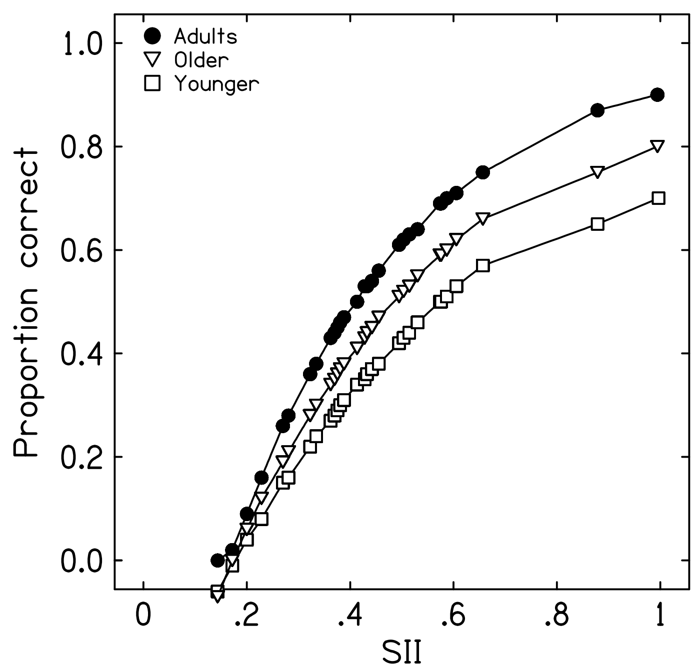

Figure 5- Tranfer function with predicted proportion correct plotted across SII derived for data from the current study for different age groups (Adults – Filled circles; Older children – open triangles, Younger children – open squares).

Phoneme errors

To determine if age-related differences in performance were related to specific patterns of phoneme errors, results from phonemic scoring were compared across age groups and conditions. Appendix C contains tables of the proportion correct for each phoneme for each age group. Appendices D, E, and F contain complete confusion matrices for each age group and filter condition. Because of large differences in the number of phoneme targets between adults (n = 1700), older children (n = 5900) and younger children (n = 5200), differences in proportion correct could not be analyzed statistically. Therefore, group differences were analyzed qualitatively. Three patterns of phoneme errors were identified. First, expected phoneme recognition based on phoneme spectral characteristics as a function of filter condition was confirmed. Next, configurations of phoneme recognition that varied across age groups were identified. Finally, phoneme recognition patterns that represented an interaction between age group and bandwidth were considered.

Errors in phoneme recognition matched predictions based on the audibility of the frequency range of their acoustic cues. Phoneme recognition declined rapidly as the frequency bands corresponding to those phonemes were filtered out of the stimuli.

Fricative perception, for example, declined rapidly for each consecutive low-pass filtering condition, as would be expected for a class of speech sounds comprised of high-frequency energy. For high-pass conditions, fricative recognition remained stable as low-frequency bands were eliminated. Conversely, vowel perception did not change significantly as a function of low-pass filter condition, but decreased significantly as the audibility of low-frequency bands was limited in high-pass conditions. Vowel confusions as a function of high-pass filtering were more prevalent for middle vowels than for point vowels.

Age-related differences in phoneme recognition helped to account for the observed age-dependency of nonword recognition. Patterns were considered to be age-related if differences across age groups were consistent across filter conditions. Recognition of stop-plosive cognate pairs /k/ and /g/ and /p/ and /b/ was higher for adults than for both groups of children. Analysis of error patterns suggested that children frequently confused /k/ and /g/ with other stop-plosive consonants, whereas /p/ and /b/ were confused with stop-plosives and fricatives, particularly /f/ and /v/. Fricatives /f/, /v/ and /θ/ also had higher recognition for adults than children across filter conditions. The nasals /n/ and /m/ showed an increasing pattern of recognition as a function of age group, wherein younger children were more likely to confuse the two phonemes than older children and adults).

Analysis of phoneme recognition also revealed patterns of confusions that reflected both age- and frequency-dependent variability. Phoneme errors were classified as both age and frequency-dependent if the pattern of results across age-group changed across filter conditions. Consistent with previous bandwidth studies (Stelmachowicz, 2001; 2002) fricative perception for younger children was poorer as low-pass filter cut-off frequency decreased. Figure 6 displays phoneme recognition for /s/ and /ʃ/, which varied as a function of age and bandwidth.

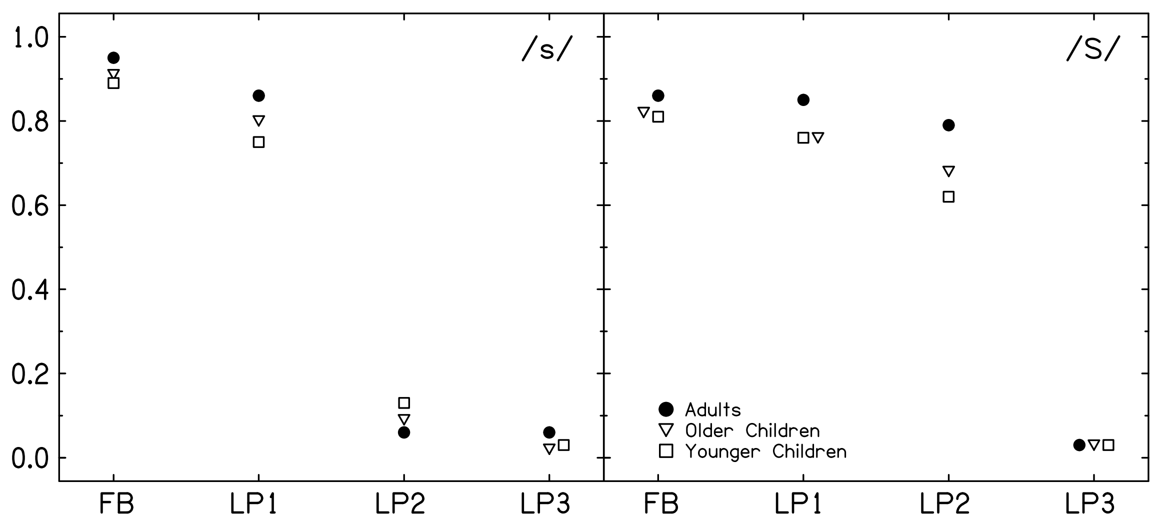

Figure 6 – Proportion of /s/ (Left panel) and /ʃ/ (Right panel) correct as a function of low-pass filter condition for different age groups groups (Adults – Filled circles; Older children – open triangles, Younger children – open squares).

However, the significance of these differences across age groups should be viewed cautiously, since these effects were not measured statistically due to large differences in sample size between adults and children

Discussion

The purpose of the current study was to evaluate predictions of speech recognition for children and adults based on the SII using nonword stimuli with limited contextual and linguistic cues. Overall, children had lower nonword recognition scores in noise than adults for the same amount of audibility as measured by the SII. Nonword recognition decreased predictably for all participants as the level of noise increased and spectral content became more limited. Despite significant differences between age groups in nonword recognition, the amount of degradation when octave bands were removed did not vary as a function of age as measured by differences in the frequency-importance weights across age groups. Age-related differences in nonword recognition are consistent with previous studies. However, the lack of differences between adults and children across conditions with varying bandwidth does not match the hypothesized effect or bandwidth effects observed for children.

Within the age range of 5 -12 years, there was additional variability in nonword recognition, with older children performing better than younger children for listening conditions with the same SII. Results from Scollie (2008) were consistent with the present findings, despite the use of different stimuli and different frequency-importance weights to calculate SII values. The present findings suggest that while the SII is useful to quantify audibility of the speech signal for children, conclusions about an individual child's speech recognition based on the SII are likely to overestimate performance unless age-specific data are used. Variability in predictions of speech recognition for children is reflected by the doubling of RMS error between predicted vs. actual speech recognition for children compared to that of adults. The observed variability within age groups may limit the applicability of age-related proficiency factors to predict speech recognition of individual children.

Similar to results from previous studies of speech recognition in children (Elliot, 1979; Johnson, 2000; McCreery et al. 2010), nonword recognition was found to follow a predictable developmental pattern with adults having higher nonword recognition scores than both age groups of children with 9-12 year-old children performing better than 5-8 year-olds. Nonword stimuli were chosen for the current study to limit the influence of lexical knowledge and the ability to use the phonotactic characteristics of the stimuli on the recognition task. However, previous studies of nonword recognition in children have demonstrated that even when linguistic and phonotactic cues are constrained, nonword recognition tasks are strongly related to expressive vocabulary ability (Metsala, 1999; Munson, Edwards & Beckman, 2005) and short-term working memory (Gathercole & Adams, 1993). In the current study, expressive language scores as measured by the Expressive Vocabulary Test were significantly correlated with nonword recognition scores. Despite attempts to limit the influence of phonotactic probability on nonword repetition in the current study, the stimulus set was sufficiently large that nonwords with a wide range of phonotactic probabilities were included in the experiment. Age-related differences in nonword recognition were likely related to a combination of vocabulary ability, short-term working memory skills and the subject's use of phonotactic probability.

Despite age-related differences in nonword recognition, the amount of degradation in nonword recognition observed when frequency bands were removed from the stimuli did not vary significantly as a function of age. This conclusion is different than the hypothesized effect of greater degradation for younger children when high-frequency spectral content was limited. In the current study, young children had poorer nonword recognition than older children and adults, but these differences were consistent across conditions of varying spectral content. Importantly, children did not experience a greater degradation than adults on average when high-frequency bandwidths were limited. Analysis of specific phoneme errors as a function of age group suggested that a wide range of phonemes from different classes including stops, nasals and fricatives contributed to age-related differences in nonword recognition. However, only perception of /s/ and /ʃ/ appeared to demonstrate frequency-dependent differences that varied across age groups. The magnitude of those differences could not be verified statistically, and even if significant are unlikely to account for the magnitude of age-related differences in speech recognition that were observed in the current study.

These results would seem to contradict a growing body of literature, including work completed in our research lab, which suggests that children may be more negatively impacted than adults when high frequency spectral content is limited. Outcome measures including speech recognition (Stelmachowicz et al. 2001) and novel word-learning (Pittman 2008) have been shown to be negatively impacted for children when spectral content is limited above 4 kHz.

Several aspects of the current study may have led to a moderation of the bandwidth effects described for children in previous studies. Age-related differences in speech recognition due to limited bandwidth have been proposed to be related to the fact that children may still be developing linguistic knowledge and skills needed for top-down processing (Stelmachowicz et al. 2004). When acoustic-phonetic representations are not accessible due to noise or limited bandwidth, adults can rely on their understanding of language, context and phonotactic probability to help recognize degraded auditory stimuli. Because children are in the process of developing these skills, acoustic-phonetic factors such as broader stimulus bandwidth and higher SNR are needed to support decoding of the speech signal. The nonword stimuli used in the current experiment were controlled to limit the use of lexical and phonotactic cues for all listeners. Because listeners had limited access to cues needed to support top-down processing, adults also relied on the acoustic-phonetic representation of the signal and their performance was more similar to the children in the current study than might be expected. Adults are likely to perform better than children with a degraded signal for stimuli with redundant linguistic cues, where knowledge of such cues would enhance speech recognition.

Additionally, the nonword CVC stimuli used in the current investigation were balanced for the occurrence of initial and final consonants in order to promote comparability with nonword stimuli used in previous studies of frequency-importance functions with adults. Most previous studies of bandwidth utilize stimuli with multiple instances of fricatives such as /s/, /ʃ/, and /f/ to provide an adequate number of exemplars to measure changes in recognition across different conditions. The limited number of high frequency phonemes in each condition may have limited the observation of a bandwidth difference between conditions with limited high-frequency spectral content. Because /s/ is the third most frequently occurring phoneme in English (Denes, 1963), it is likely that a stimulus set with a more realistic balance of phonemes could reflect the pattern of results observed in previous studies of the effects of bandwidth on speech recognition and word learning in children.

The frequency-importance weights derived for both children and adults in the current experiment are similar to those obtained with nonwords with phonemes occurring in equal frequencies that are used as the basis for the nonword importance weights in the ANSI standard. Two octave bands in the current study show different importance weights than the ANSI standard nonword weights. The importance weight for the 8000 Hz band is higher than previous octave-band weights for nonwords (Duggirala et al. 1988). The difference is likely reflective of the use of female talkers with greater spectral content in that frequency band than the male talkers that were used in previous studies. These spectral differences are apparent in Figure 1. Additionally, the 500 Hz band importance weight was significantly less than has been observed in previous studies. Differences in the long-term spectral characteristics between the female talkers in the current study and spectrum of the male talkers used in previous studies are not sufficient to explain the differences observed in the current study. However, significant variability in speech recognition for adults in high-pass filtered listening conditions have been reported in previous studies (Miller & Nicely, 1955). Because acoustic cues that signify place, manner and voicing occur in the low frequencies, the error patterns are much less consistent and predictable for high-pass filtered conditions than low-pass filtered conditions. Therefore, other characteristics of the current stimulus set may have limited the importance of the 500 Hz band for all three age groups compared to previous studies.

Limitations and Future Directions

Several important limitations of the current study should be considered when comparing the results to previous studies and planning future research in this area. While efforts to limit the task demands on children in the current study are important, the decision to have each subject listen to half of the potential conditions increased the variability of the results and limits the comparability of these findings to those obtained with subjects listening to all possible conditions. While the use of nonword CVCs allows the limitation of the influence of linguistic and phonotactic cues on speech recognition, these stimuli are likely to represent only a worst-case scenario to speech recognition, as even young children are able to use limited linguistic cues to support speech recognition (Boothroyd & Nittrouer, 1990). The pattern of results is likely to vary if linguistic context is provided, and future studies should attempt to evaluate the role that these cues play in supporting speech recognition in children when spectral information is limited. Because the differences in performance between adults and children were not frequency-dependent, as evidenced by similar frequency-importance functions across age groups, future studies should attempt to determine a potential mechanism, such as differences in short-term working memory that may account for age-related differences in nonword recognition.

Conclusion

The aim of the current study was to evaluate predictions of children's speech recognition based on audibility as measured by the SII. Children between 5 and 12 years of age with normal hearing had poorer nonword recognition for listening conditions with the same amount of audibility compared to the performance of adults on the same task. However, contrary to previous studies, children did not experience greater degradation in speech recognition than adults when high-frequency spectral content was limited. The fact that adults and children both performed more poorly for band-limited conditions with stimuli with limited linguistic cues supports the importance of high-frequency audibility in conditions where context is limited. This is particularly true for young children who may be developing linguistic knowledge and improving efficiency of related cognitive processes. The SII provides an estimate of audibility, but use of the SII to predict speech recognition outcomes in children should take into account the potential variability both between adults and children and within children of the same age that were observed in the current investigation.

Chapter 3 - The effects of limited bandwidth and noise on working memory and listening effort in normal-hearing children

Introduction

The ability to comprehend speech requires the listener to use a combination of the audible acoustic-phonetic cues from the stimulus, often called bottom-up factors, and the listener's cognitive skills and knowledge of language and context, known collectively as top-down factors. Depending on the demands of a particular listening environment, contributions of both bottom-up and top-down processes may be used to decode the speech signal. For example, the presence of background noise or other forms of signal degradation places greater demands on a listener's top-down skills and resources (see Jerger, 2007 for a review). Adults typically have fully functional cognitive and linguistic abilities to support listening in difficult environments, as evidenced by the ability to understand sentences even at a negative signal-to-noise ratio (SNR; Nillson et al 2004).

Children, however, are still developing both the cognitive operations and knowledge required to understand language. Thus, their speech understanding is likely to be more negatively impacted when the audibility of the acoustic-phonetic representation of the stimulus is degraded by noise or limited bandwidth. Evidence of this effect has been widely reported in studies of speech recognition in children. Compared to adults, children require more favorable SNRs (Elliot, 1979; Johnson, 2000; Hnath-Chisolm et al. 1998; McCreery et al. 2010), broader bandwidth (Stelmachowicz et al. 2001; 2002, Mlot, Buss & Hall, 2010), preserved spectral cues (Eisenberg et al. 2000) and less reverberation (Neuman et al. 2010) to reach maximum levels of speech recognition. However, typical measures of speech perception do not necessarily reflect the impact of acoustic distortions of the speech signal on higher-order cognitive processes required for learning. Despite the importance of evaluating the effects of limited audibility on the underlying cognitive processes that facilitate communication development in children, relatively few studies have examined this relationship. While the ability to recognize speech is an important antecedent to word learning and vocabulary development, recognition of acoustic cues on a speech perception task is not sufficient to demonstrate that a child is able to use such cues linguistically. This point is highlighted by Stelmachowicz et al. (2002), who cautioned against the inference that recognition of phonemes such as /s/ and /z/ that can be used as inflectional morphemes reflects comprehension of the function of those sounds in a particular context. The goal of the present study was to further examine of how acoustic distortions of the speech signal by noise and a restricted bandwidth affect normal-hearing children's speech recognition and aspects of auditory learning, such as memory and cognitive processing.

The importance of characterizing the effects of audibility on learning and cognitive processes has been highlighted by studies of the acoustic characteristics of classroom environments. Knecht and colleagues (2002) measured ambient noise levels in thirty-two unoccupied elementary school classrooms and found that the classrooms had a wide range of ambient noise levels, but that only four were within the limits recommended by the ANSI standard for classroom acoustics. The presence of noise in classrooms is a common problem. Further investigation of the impact of classroom noise levels on speech recognition in children revealed that the levels of noise in typical classrooms can interfere with speech understanding for children with normal hearing (Bradley & Sato, 2008). Children with hearing loss experience even more significant reductions in speech recognition in background noise than their normal-hearing peers (Dubno, Dirks & Morgan, 1984). Additional limitations on the bandwidth of the speech spectrum are imposed on children who wear hearing aids (Boothroyd & Medwetsky, 1994). Both background noise and bandwidth have the potential to distort the speech signal and make cognitive processing more challenging.

Previously, the influence of audibility on the cognitive processes related to speech recognition has been explored using three general types of outcomes: reaction time, measures of short-term or working memory, and word learning. Reaction time is generally defined as the amount of time that it takes to perform a task and has been used to quantify a wide range of mental operations including memory (Cowan et al. 2003), lexical processing (Yap & Balota, 2007), and attention (Weiler et al 2002). Studies of verbal response have been used in speech recognition paradigms to estimate the amount of cognitive effort required to listen under different conditions (Gatehouse & Gordon, 1990; Mackersie, Neuman & Levitt, 1999). As listening conditions become more difficult, the amount of time that it takes to respond to the stimulus is expected to increase, reflecting greater reliance on lexical access, memory and other top-down processing strategies as the acoustic representation of the stimulus is degraded.

The ability to temporarily hold phonological representations of words for storage and processing, known as working memory (Atkinson & Shiffrin, 1968), is an important component in the ability to comprehend and learn language (Gathercole, 2006).

Baddely and Hitch (1974) proposed a specialized system of auditory-verbal memory called the phonological loop. The phonological loop acts as short-term storage for auditory information and provides the basis for the development of phonological representations of new words (Baddely, Gathercole, & Papagno, 1998). Gathercole (2006) has proposed that speech recognition for nonword stimuli and the ability to learn new phonological representations of words are strongly related, as both are dependent upon the function of the phonological loop in developing short-term representations of stimuli. Evidence for the relationship between nonword repetition tasks and word learning was reported in a longitudinal study by Majerus and colleagues (2006) who found that performance on a nonword recognition task by four year-olds predicted vocabulary at age five. More recently, Majerus et al. (2009) used a serial recall task with nonword stimuli and an attention task to demonstrate the relationship between nonword recall, attention and vocabulary development in children. These studies suggest that nonword recognition, short term memory and language learning are related to a common, cognitive process.

Because intact phonological representations are necessary for word learning, interference from environmental noise or limited bandwidth could reduce the ability of children to attend to and store these representations. Research by Surprenant (2007) measured word recognition and recall in background noise with adult listeners and found that recall was inhibited by noise, even when the level of the noise was not sufficient to impact recognition. Children are likely to be more susceptible to interference from background noise and limited bandwidth because auditory recognition is the first stage in engaging short term memory. Decreased accuracy on speech recognition tasks in background noise by children is likely to impact the accuracy of representations in working memory. To date, the influence of background noise or limited bandwidth on measures of short-term memory in children has not been directly evaluated.

Rapid word-learning tasks have also been used to explore how audibility constraints related to hearing loss and limited bandwidth might influence communication outcomes. Pittman and colleagues (2005) used a rapid word-learning paradigm, known as fast-mapping, to examine the factors that affect word learning in children with hearing loss, who frequently have impoverished vocabularies compared to children of the same age with normal hearing. Results revealed that while children with hearing loss had poorer performance than normal hearing children on the word-learning task, neither group of children performed better when the bandwidth of the stimuli was extended from 4 kHz to 9 kHz. The authors concluded that the lack of benefit from extended bandwidth for word-learning may have been related to the limited number of exposures the subjects received during the experiment. Pittman (2008) extended the previous study using a fast-mapping task with 30 repetitions of five novel words in an attempt to determine if a greater number of exposures would result in differences between limited and extended stimulus bandwidth. Children with hearing loss and children with normal hearing who completed the word-learning task in an extended bandwidth condition performed better than groups of children with the same hearing status who completed the task under a limited bandwidth condition. These results support the possibility that the benefits of a broader bandwidth for children may extend beyond speech recognition to positively impact underlying processes of speech and language learning.

Although evidence suggests that rapid word-learning can be negatively affected by hearing loss and limited bandwidth, several questions regarding the underlying mechanism of these effects remain unresolved. While word-learning paradigms can be used to estimate the rate of novel word-learning, such tasks do not directly assess the effect of acoustic degradation on children's general working memory with words that are already in their lexicon. While children have difficulty learning novel words in background noise or with a restricted bandwidth, the process of recalling acoustically corrupted words may be easier for children because they can use phonological and lexical knowledge to integrate the information held in the phonological loop. The effect of improved recall for known words compared to nonwords is referred to as the lexicality effect and is supported by studies which have compared recall using stimuli with differing lexical characteristics (Roodenrys & Hinton, 2002; Gathercole et al. 2001). Additionally, Gathercole and colleagues (1999) found that even for nonword stimuli, children were able to utilize their knowledge of phonotactic probabilities to bolster their performance in a recall task. These results suggest that children may be able to use both lexical and phonological knowledge to support recall when acoustic conditions are suboptimal. However, this hypothesis has not been tested directly for recall with background noise or reduced bandwidth.

In the current study, two different tasks were used to evaluate the influence of noise and stimulus bandwidth on working memory in children. In one task, children were required to repeat nonword consonant-vowel-consonant (CVC) words in various conditions of noise and a range of stimulus bandwidths. Nonword recognition accuracy and verbal response time were measured to determine the influence of noise and restricted bandwidth on short-term phonological memory. Nonword recognition has been proposed to be similar to a serial recall task with the order and accuracy of phonemes being recalled (Gupta, 2005). The other task consisted of free item recall of real words that were developed specifically for testing speech recognition in young children (Haskins, 1948). Word recognition and recall accuracy were measured under similar conditions of limited bandwidth and noise. Children were expected to demonstrate a decrease in nonword recognition performance and an increase in verbal response time as a function of decreasing SNR and bandwidth. For the recall task, children were expected to be able to utilize lexical and phonotactic cues to support recall under degraded conditions. Listening conditions for both tasks were designed to reflect a realistic SNR that would be experienced in classroom settings, as well as the typical bandwidth reduction that would be experienced by a child with hearing loss using a modern hearing aid.

Method

Participants

Twenty-one children between the ages of 6 years, 10 months and 12 years, 11 months (Mean = 9 years, 3 months) participated in the current study. Subjects were recruited from the Human Research Subject Core at Boys Town National Research Hospital. Participants were paid $12 per hour and given a book for their participation. All listeners had clinically normal hearing in the test ear (15 dB HL or less) as measured by pure tone audiometry at octave frequencies from 250 Hz – 8000 Hz. Two children did not meet the audiological criteria for the study and were excluded from participation. None of the participants or their parents reported any history of speech, language or learning problems. Children were screened for articulation problems that could influence verbal responses using the Bankson Bernthal Quick Screen of Phonology (BBQSP; Bankson & Bernthal, 1990). The BBQSP is a clinical screening test that uses pictures of objects to elicit productions of words containing target phonemes. One child did not pass the age-related screening criterion and did not participate in the study. Receptive language skills were measured for each participant using the Expressive Vocabulary Test, Form B (EVT; Williams, 2007). All of the children in the study had standard scores within two SD of the normal range for their age [Mean = 101; Range = 86-108].

Stimuli

All stimuli were spoken by an adult female talker and digitally recorded. Nonword CVC stimuli with a limited range of phonotactic probability that were developed for another study were used for the nonword recognition task. Development and characteristics of these stimuli were discussed in the previous chapter. Recordings of monosyllabic real words from the Phonemically-Balanced Kindergarten (PBK-50; Haskins, 1948) were used for the free recall task. Because of previous studies that have shown an impact of phonotactic probability (Gathercole et al. 1999) and word frequency (Hulme et al. 1997) on working memory tasks, the phonotactic probabilities and word frequencies of the nonwords were entered into an online calculator based on the Child Mental Lexicon (CML; Storkel & Hoover, 2010) in order to specify these characteristics for later analyses (See Appendix A). Speech-shaped competing noise was created by taking the Fast Fourier Transform (FFT) of the long-term average speech spectrum of the talker, randomizing the phase at each sample point, and taking the inverse FFT of the resulting stimulus. The result is a noise with the same spectral shape as the talker, but without spectral and temporal dips. The bandwidth of the stimuli was limited using infinite-impulse response (IIR) Butterworth filters in MATLAB. Table 4 displays the bandwidth of the listening conditions. The filtering was limited to low-pass filtering to reflect the degree of bandwidth restriction that would be typically experienced by a child wearing a hearing aid. The Speech Intelligibility Index (SII) of all conditions was calculated using an octave band method for a nonreverberant environment.

Table 4. Filter conditions.

Condition	**Frequency range**
Full band (FB)	0 - 11025 Hz
Low-pass (LP)	
LP1	0 - 5600 Hz
LP2	0 - 3200 Hz

Instrumentation

Stimulus presentation, including control of the levels of speech and noise files during the experiment, and response recording was performed using custom software on a personal computer with a Lynx Two-B sound card. Sennheiser HD-25-1 headphones were used for stimulus presentation. A Shure head-worn boom microphone was used to record subject responses for later scoring. Pictures were presented via a computer monitor during the listening task to maintain subject interest during the listening task. The sound levels of the speech and noise signals were each calibrated using a Larson Davis (LD) System 824 sound level meter with a LD AEC 101 IEC 318 headphone coupler. Prior to data collection for each subject, the sound level was verified by playing a pure tone signal through a voltmeter and comparing the voltage to that obtained during the calibration process for the same pure tone.

Procedure

Participants and their parents took part in a consent/assent process as approved by the Institutional Review Boards of Boys Town National Research Hospital and The University of Nebraska-Lincoln. All of the procedures were completed in a sound-treated audiometric test room. Pure tone audiometric testing was completed using TDH-49 earphones. The children completed the BBQSP and EVT. For the nonword recognition and recall tasks, participants were seated at a table in front of the computer monitor. The order of the tasks was counter-balanced across subjects to limit potential influences of fatigue and attention on a particular task.

For the nonword recall task, the children were instructed that they would hear lists of words that were not real words and to repeat exactly what they heard. Participants were encouraged to guess if they were not sure what they heard. Each subject completed a practice trial in the full bandwidth condition without noise to ensure that the subject understood the task and directions. Following completion of the practice trial, the filtered speech recognition task was completed in noise using one 25-item list per condition. List number, filter condition and SNR were randomized using a random sequence generator. The presentation order of the stimuli within each list was also randomized. Although feedback was not provided on a trial-by-trial basis, children were encouraged regardless of their performance after each list. Each subject listened to six experimental conditions comprised of three different bandwidths (FB, LP1, and LP2) at two SNRs (+3 and +9 dB). For the free recall task, children were instructed to listen for and repeat back the real words that they heard. After a block of five words, the child was asked to repeat as many of the words as they could remember. Each condition used 25 words for a total of 5 recall blocks per condition. A practice condition in quiet was completed with each subject to ensure that they understood the task and directions. Following completion of the practice condition, word recognition and free recall were measured at the same SNR (+9 dB) for the FB and LP1 bandwidth conditions. The entire process took approximately 90 minutes per subject.

Responses for nonword and real word recognition were coded online during the task as correct and incorrect. Free recall and verbal response time were scored offline using recordings of the test session. Online scoring of correct or incorrect responses was also cross-checked offline. For free recall, if a child made a word recognition error, but correctly recalled the errant response, the response was counted as correct for their recall score. Verbal response time was estimated by custom software designed to measure the latency between the onset of the stimulus and the onset of the subject's response for each token. Given the potential for phonemic bias against phonemes with spectral characteristics similar to the background noise used in the experiment, such as fricatives (Kessler et al. 2002), verbal response times for each token were verified by visual inspection of the waveform.

Results

Nonword recognition and verbal response time

Prior to statistical analysis, proportion correct nonword recognition scores were converted to Rationalized Arcsine Units (RAU; Studebaker, 1985) to normalize variance across conditions. Additionally, verbal response times less than 250 ms or greater than 3000 ms were eliminated as being either fast guesses or inattentive responses, respectively (Whelan, 2002). This process led to the elimination of 55 verbal response times (2%) out of 2550 total responses. Mean nonword recognition as a function of condition is plotted in Figure 7, while mean verbal response time as a function of condition is plotted in Figure 8.

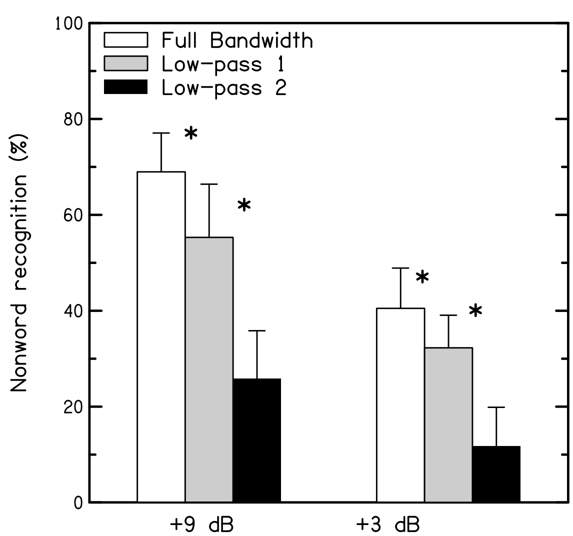

Figure 7 – Nonword recognition (percent correct) as a function of condition (White bars – Full bandwidth; Gray bars Low-Pass 1, Black bars Low-Pass 2) for +9 and + 3 dB signal-to-noise ratios.

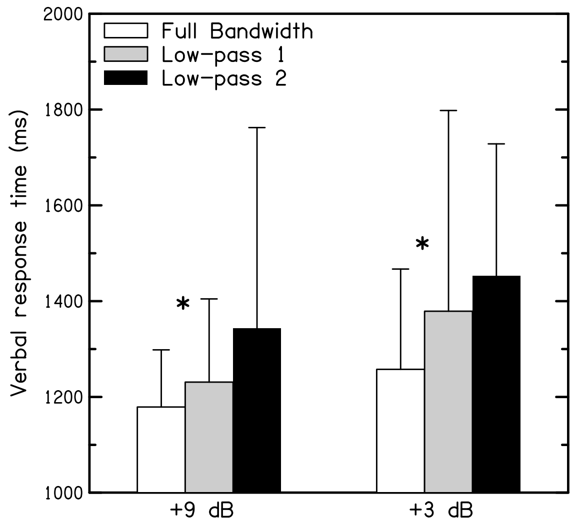

Figure 8 – Verbal response time (ms) as a function of condition (White bars – Full bandwidth; Gray bars Low-Pass 1, Black bars Low-Pass 2) for +9 and + 3 dB signal-to-noise ratios.

The general trend in the data supports the hypothesized effect of decreasing nonword recognition and increasing verbal response time as audibility decreases due to both SNR and bandwidth restriction. To evaluate if these trends in nonword recognition and verbal response time were statistically significant, repeated-measures ANOVAs were completed with SNR and bandwidth as factors for each dependent variable. For nonword recognition, the main effects of bandwidth ($F\ (2,32) = 142.982$, $p < 0.001$, $\eta^2_p = 0.899$) and SNR ($F\ (1,16) = 92.278$, $p < 0.001$, $\eta^2_p = 0.852$) were statistically significant. The two-way interaction between Bandwidth and SNR was not significant ($F\ (2,32) = 1.075$, $p = 0.370$, $\eta^2_p = 0.060$). Evaluation of the marginal means for SNR revealed the anticipated effect of significantly higher nonword recognition for the +9 dB SNR relative to the + 3 dB SNR. To evaluate the source of the significant difference in nonword recognition for bandwidth, post hoc testing was completed using Tukey's Honestly Significant Difference (HSD) with a calculated significant minimum mean difference of 9.47 RAU. Decreasing nonword recognition was observed across each condition of limited bandwidth, and the differences between FB and LP1 (10.669 RAU) and LP1 and LP2 (28.977 RAU) were both significant when controlling for Type I error.

The pattern of statistical results for verbal response time was similar to that observed for nonword recognition across conditions. The main effects of SNR ($F(2,32) = 12.432$, $p < 0.001$, $\eta^2_p = 0.437$) and bandwidth ($F(1,16) = 9.727$, $p = 0.007$, $\eta^2_p = 0.378$) were significant with no significant two-way interaction between SNR and bandwidth ($F(2,32) = 0.384$, $p = 0.684$, $\eta^2_p = 0.023$). Evaluation of the marginal means for SNR revealed the anticipated effect of significantly reduced verbal response time for the +9 dB SNR compared to the +3 dB SNR. To evaluate the source of the significant difference in verbal response time for bandwidth, post hoc testing was completed using Tukey's Honestly Significant Difference (HSD) with a calculated significant minimum mean difference of 90.5 ms. Increasing verbal response time was observed across each condition of limited bandwidth, and the difference between the FB and LP1 (86.762 ms) was significant, while the difference between LP1 and LP2 (93.162 ms) was not significant when controlling for multiple comparisons. In summary, nonword recognition and verbal response time were both negatively impacted by noise and restricted bandwidth.

Word recall

Mean word recognition accuracy and free recall accuracy are plotted as a function of bandwidth condition in Figure 9.

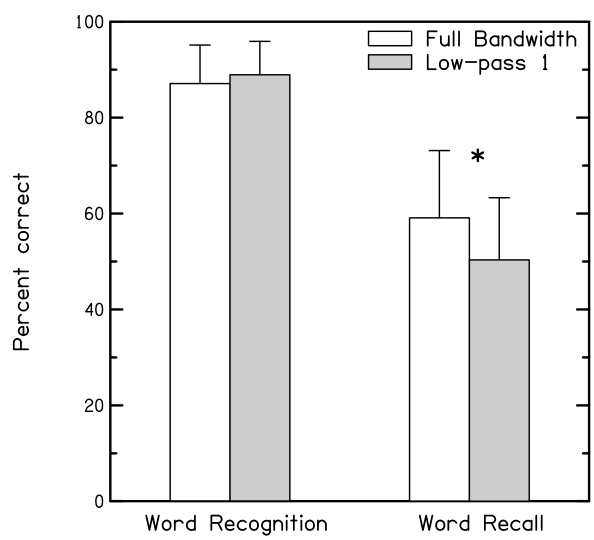

Figure 9 – Word recognition and word recall (percent correct) as a function of stimulus bandwidth (White bars – full bandwidth; Gray bars – Low-pass one) for a +9 dB SNR signal-to-noise ratio.

While there was no difference between the average word recognition score for each bandwidth condition, higher word recall was observed for the full bandwidth condition than for the low-pass filtered condition. Because word recognition and word recall were not independent as they were derived from the same task, a multivariate analysis of variance (MANOVA) for repeated-measures for word recognition and word recall was completed with bandwidth as a factor. The multivariate effect of bandwidth on the combined effect of word recognition and recall was significant (Wilks $\lambda = 0.572$; $F = 5.614$, $p = 0.015$, $\eta^2_p = 0.378$). The univariate test for word recognition revealed no significant differences between bandwidth conditions ($F(1,16) = 0.715$, $p = 0.410$, $\eta^2_p = 0.043$), whereas the univariate test for recall indicated a significant difference in recall between bandwidth conditions ($F(1,16) = 10.188$, $p = 0.006$, $\eta^2_p = 0.389$). Overall, there was no difference in word recognition between full bandwidth and low-pass filtered conditions, but recall was significantly higher in the full band condition compared to the low-pass filtered condition.

Due to the wide range of performance observed in recall ability across subjects, a linear regression analysis was conducted to evaluate age and expressive vocabulary scores (EVT) as predictors of recall. The bivariate correlation between age (in months) and EVT standard score was not significant ($r = 0.169$, $p < 0.518$). A regression model with age as a predictor of recall revealed age as a significant predictor of recall ($R^2 = 0.294$, $F(1,15) = 6.240$, $p = 0.025$). EVT standard score was added as an additional predictor resulting in a model that accounted for more variance than the nested model with age as the only predictor ($R^2 = 0.365$, $F(2,14) = 4.022$, $p = 0.043$). However, the change in R^2 between the model with age as the only predictor and age and EVT standard score was not significant based on Fisher's Z test (R^2 change $= 0.071$, $p = 0.231$), suggesting that for this group of subjects, age in months predicted as much variance in recall as age and EVT standard score.

Discussion

The goal of the current study was to evaluate the effects of noise and limited bandwidth on two tasks of auditory working memory in children. The main hypothesis was that nonword recognition would be more susceptible to interference from background noise and limited bandwidth than recall of real words. The lexical and phonological representations in long-term memory were expected to support recall performance for words more than nonwords. Nonword recall and verbal response time were measured in six conditions using three different bandwidths and two different SNRs. For the nonword task, both nonword recognition accuracy and verbal response time were affected by noise and limited bandwidth. Nonword recognition accuracy decreased, whereas verbal response time increased and became more variable, suggesting greater listening effort as the acoustic stimulus became more degraded. Free recall for real words was determined in a separate task. For the word recall, there were no significant differences in word recognition between bandwidth conditions, but recall was significantly higher in the full bandwidth condition than in the low-pass filtered condition.

Findings from both tasks generally fit the predictions of Gathercole's (2006) model of the phonological loop as a mechanism for verbal working memory. The model predicts that nonword recognition and short-term recall both engage the phonological loop in working memory and that children's memory performance is susceptible to interference at the stages of the model where the stimulus is encoded during auditory perception. The effects of limited audibility were consistent across both nonword recognition and word recall with lower performance for both variables as audibility was reduced. Reduced recall for real words by children in the current study was not anticipated, as previous studies have demonstrated that recall performance is better for real words than for nonwords (Hulme et al. 1997). However, in the current investigation word recall and nonword recall were not evaluated using the same task. Pilot testing of nonword recall under conditions of limited bandwidth and noise revealed that the task was too difficult for children to perform. Because of this limitation, the current results should not be considered as evidence against a lexicality effect for children's working memory.

Word recall results in the current study also have practical implications outside of the theoretical questions regarding lexicality effects for working memory in children. First, recall of real words was negatively affected by limited bandwidth. The differences in audibility between the two conditions of the recall task as measured by the Speech Intelligibility Index (SII; Full bandwidth = 0.6566; Low-pass 1 = 0.6249) was minimal. The limited loss of audibility when the 8000 Hz band is filtered out is evident by the lack of change in word recognition for that condition. Despite the lack of change in word recognition, recall decreased with this small change in audibility. This particular low-pass filter condition was selected as it approximates the loss of bandwidth that is experienced by children with hearing loss when using a conventional hearing aid. Decrements in recall related to small changes in audibility, even for conditions where recognition is not affected, suggest that speech recognition alone does not reflect how audibility can influence cognitive processing of auditory stimuli in children.

Although the present findings obtained from children with normal hearing cannot be generalized to children with hearing loss, previous studies of rapid word learning (Pittman, 2008) and listening effort (Hicks & Tharpe, 2002) comparing children with hearing loss to children with normal hearing would suggest that differences in audibility could reduce word learning or recall of known words by children with hearing loss. The current study did not include tasks that could be considered tests of novel word-learning abilities in normal-hearing children, but the results are congruent with the reduced novel word learning observed by Pittman (2008) for conditions of limited bandwidth. Specifically, decreased nonword recognition and word recall in the current study reflect the same interference in the phonological loop of working memory that results in a greater number of exposures for novel words that have reduced bandwidth. The point in the process where the interference occurs remains unresolved. For example, noise and limited bandwidth could interfere with the auditory perception of the stimulus, development of a phonological representation of the stimulus in the phonological loop, or the rehearsal or encoding of the stimulus. The fact that decreased performance was observed for word recall in the current study when recognition of those words was not affected suggests that the affects of noise and bandwidth are not limited to the auditory perception stage of the process.

Limitations and directions for future research

Several limitations should be considered when evaluating the current results. The findings of the current study are based on a small group of children with normal hearing with a limited range of normal expressive language abilities. An investigation of the relationship between bandwidth and working memory in children with hearing loss would be more realistic than the current investigation with children with normal-hearing, as children who do not use hearing aids rarely experience limited bandwidth in everyday situations. The extent to which these findings would generalize to a larger sample, including children with hearing loss, is unclear and should be evaluated in future studies. Although lexicality has been shown to influence short-term auditory memory with children in previous studies, the different tasks used for words and nonwords do not allow for a direct comparison of this effect in the current study. The relationship between nonword recognition and working memory in children is supported by previous studies, and the results of the current investigation follow the predictions of theoretical models of memory in children. However, the pattern of findings should be replicated using different tasks of working memory in children such as serial recall, which may have more direct implications for realistic situations.

Conclusion

The current study sought to describe the affects of noise and limited bandwidth on working memory for normal-hearing children using both real words and nonwords. Nonword recognition and verbal response time were negatively affected by both background noise and limited bandwidth. For real words, recognition was not affected by bandwidth, but recall was significantly poorer when the bandwidth of the stimulus was limited above 5000 Hz. These results suggest that acoustic degradation of the speech stimulus not only influences auditory recognition, but also the process of committing these stimuli to memory. Working memory abilities have significant implications for the ability to learn new words, as well as academic learning. Future studies should evaluate if similar effects are observed in children with hearing loss.

Chapter 4 - Summary

Two studies were conducted with the overall goal of testing hypotheses related to speech recognition, working memory and listening effort in children. Methods of calculating limitations in audibility due to background noise or hearing loss are based on data from adult listeners. Previous studies have suggested that children may require greater audibility than adults to compensate for differences in cognitive processing and speech and language skills that occur during development. Although such differences are likely to have significant clinical implications for estimating audibility and speech recognition in children, few studies have systematically examined the complex interactions between audibility, speech recognition, and auditory cognitive processes in children.

In the first study, the main hypothesis was that predictions of speech recognition based on the Speech Intelligibility Index (SII) would overestimate performance in children with normal hearing. Specifically, frequency-importance weights and derived transfer functions were explored as potential sources of age-related variance in the SII calculation. While transfer functions varied between adults and children and between groups of older and younger children, frequency-dependent differences in performance were not observed. Further exploration of the phoneme errors as a function of age group revealed that age-related differences in nonword recognition between adults and children were potentially related to age-dependent differences in phoneme recognition, as well as age- and frequency-dependent interactions for fricative sounds. Differences in cognitive variables such as working memory that vary within the age range of children in the study were also posited as explaining age-related variance in nonword recognition.

To explore how working memory may have resulted in age-dependent changes in the first experiment, two tasks designed to assess the phonological loop of working memory (Baddely & Hitch, 1974; Gathercole, 2006) were completed with normal-hearing children. Nonword recognition and verbal response time were measured across six conditions of noise (+9 / +3 dB SNR) and limited bandwidth (full bandwidth, 0 – 5600 Hz, and 0 – 3300 Hz) to assess the impact of limited audibility on working memory. To determine if children could use lexical knowledge to improve memory performance in conditions of limited bandwidth, free recall of real words was completed at a fixed SNR for two conditions of bandwidth (full bandwidth and 0 – 5600 Hz). Nonword recognition decreased and verbal response time increased as audibility was limited by noise and restrictions in bandwidth. Recognition of real words was not negatively affected for a fixed SNR and limited bandwidth, but recall of real words was poorer when bandwidth was limited. These results suggest that recognition tasks are not adequate to predict working memory performance in children and that limited audibility may impact the ability to commit stimuli to memory, even if recognition is relatively intact.

The current studies have important implications for clinical estimation of audibility and speech recognition for children using the SII. The underlying assumption of the SII is that if speech is audible to the listener, they will have the linguistic and cognitive skills necessary to interpret the stimuli and incorporate those representations into long-term memory. Children continue to develop the necessary skills for speech recognition through adolescence. Therefore, models of estimating audibility in children should take into account this variability by using data derived from large numbers of children for a wide range of speech stimuli of varying linguistic complexity.

Until such data can be obtained, children should receive the benefit of optimizing their listening environments and assistive technologies to maximize speech audibility. For children with normal hearing, reductions in ambient noise in their environments, particularly in classrooms, is critical for maximizing learning. Children with hearing loss face additional challenges related to the bandwidth of conventional hearing aids, as well as compounding effects that may result from distorted acoustic-phonetic representations of the stimulus and communication deficits. Maximizing audibility for children with hearing loss may require advances in technology, such as frequency-lowering hearing aids or hearing aids with extended bandwidths.

Overall, limitations in audibility due to background noise and limited bandwidth have negative effects on speech recognition and working memory in children. Deficits in working memory were observed even under conditions where recognition was preserved. This finding suggests that limited speech audibility may constrain working memory at levels of processing beyond auditory perception. Future studies should seek to integrate current models of speech recognition, working memory, word-learning to help maximize speech and language outcomes for children with hearing loss.

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APPENDIX A – Key to Klattese symbols and International Phonetic Alphabet (IPA) Equivalents

Consonants	
IPA	Klattese
p	p
t	t
k	k
b	b
d	d
g	g
ʧ	C
ʤ	J
s	s
ʃ	S
z	z
ʒ	Z
f	f
θ	T
v	v
ð	D
h	h
n	n
m	m
ŋ	G

Vowels	
IPA	Klattese
i	i
ɪ	I
ɛ	E
e	e
œ	@
ɑ	a
ʌ	^
o	o
ʊ	U
u	u

APPENDIX B – CVC Nonword Lists with Phonotactic Probabilities

List 1		**List 2**		**List 3**	
Klattese	Biphone sum	Klattese	Biphone sum	Klattese	Biphone sum
boJ	0.0041	boS	0.0043	bep	0.0048
CIS	0.0058	Cin	0.0054	C^d	0.0029
DEp	0.0036	diC	0.0035	Cam	0.0053
D@v	0.0029	deT	0.0031	dEm	0.006
d@z	0.0054	Dot	0.0043	DIS	0.0038
fIJ	0.0058	fad	0.0056	D@T	0.0031
f^f	0.0041	fis	0.0045	deZ	0.003
gEp	0.0031	gov	0.0036	fiC	0.0039
hus	0.0032	gop	0.0044	g@z	0.0031
Jos	0.0049	hof	0.0043	hiC	0.0036
J^z	0.0046	Jod	0.0033	J@C	0.0044
k^T	0.0052	J@J	0.003	JIT	0.003
mob	0.0046	kEp	0.0044	kit	0.0059
miD	0.0031	meG	0.0038	miS	0.0032
nEm	0.0041	mEJ	0.0056	nED	0.0032
n^g	0.0038	n^s	0.0052	nov	0.0038
pEC	0.0048	nig	0.0032	pEf	0.0059
Sun	0.0039	poJ	0.0042	seG	0.0032
seS	0.0035	Sab	0.0059	SaJ	0.0031
sov	0.004	SaD	0.0032	Sas	0.0039
Set	0.0046	sep	0.0049	tIb	0.0044
t^d	0.0051	tiZ	0.0035	T^f	0.0031
TEk	0.005	taz	0.003	tuG	0.0037
vEv	0.004	T^k	0.0043	vem	0.0034
zIf	0.0034	vIf	0.0038	zip	0.0033
Mean	**0.004264**	**Mean**	**0.004172**	**Mean**	**0.00388**

List 4		List 5		List 6	
Klattese	Biphone sum	Klattese	Biphone sum	Klattese	Biphone Sum
bom	0.0055	biv	0.0057	boC	0.0042
Ceb	0.0034	CEf	0.0031	CIC	0.0048
D@g	0.0043	C@T	0.0033	Det	0.0043
daz	0.0053	deC	0.003	dEz	0.0043
fof	0.0056	dib	0.0029	f^b	0.0055
f^G	0.0054	D@b	0.0035	foT	0.0057
gaD	0.0047	f@J	0.0034	fiv	0.0039
hav	0.0047	fep	0.0035	gin	0.0044
JEp	0.0047	f@z	0.004	h^D	0.005
Jes	0.0057	g^d	0.0042	JEg	0.0044
kET	0.003	his	0.0042	JEG	0.0031
mog	0.0043	J^C	0.0035	k^J	0.0051
m^T	0.006	Jik	0.0038	miv	0.0044
n@C	0.0037	k^D	0.0053	mig	0.0035
noJ	0.0033	meJ	0.0043	nif	0.0033
put	0.0032	nog	0.0041	n^f	0.0036
SaS	0.0029	nIS	0.0059	pem	0.006
sob	0.0046	pun	0.004	Ses	0.0056
Tid	0.0043	S@f	0.0035	siZ	0.0041
taD	0.0034	soJ	0.0035	S@v	0.0033
tuf	0.0041	tav	0.0029	TId	0.0058
t^v	0.0047	Toz	0.003	tob	0.0046
T@b	0.0029	teS	0.0029	toS	0.0037
vId	0.0053	vos	0.0035	v@T	0.0038
zuz	0.0029	zup	0.0029	zoz	0.003
Mean	**0.004316**	**Mean**	**0.003756**	**Mean**	**0.004376**

List 7		List 8		List 9	
Klattese	Biphone sum	Klattese	Biphone sum	Klattese	Biphone sum
biS	0.0045	bob	0.0052	bUt	0.0036
Cem	0.0037	CEm	0.0036	Cun	0.0042
Cup	0.0036	D@C	0.0032	CIT	0.0036
D@d	0.006	dok	0.0056	doC	0.0029
Dem	0.0041	doS	0.003	def	0.0037
dep	0.0047	fEJ	0.0037	Des	0.0053
deJ	0.0035	fEp	0.0048	fEm	0.0049
fED	0.004	g@C	0.0039	fip	0.0053
gid	0.0043	g^b	0.0056	gob	0.0042
ges	0.0053	hET	0.0055	gIS	0.0048
hog	0.005	Jeb	0.0042	hep	0.0032
J@v	0.0041	J^G	0.0054	Jev	0.0054
keT	0.0029	kED	0.0036	J^d	0.0041
miC	0.0044	mEG	0.0051	mof	0.0036
miz	0.0052	nIv	0.0047	nIJ	0.0029
n^p	0.0041	pef	0.004	nob	0.0044
n@v	0.0034	pET	0.0049	pof	0.0043
pib	0.0048	sif	0.0048	S^b	0.0044
piZ	0.0039	SIg	0.006	SEm	0.0042
S@C	0.0036	Sos	0.0047	suZ	0.0035
suf	0.0038	tud	0.0056	t^D	0.0035
t@C	0.0052	tuZ	0.0038	T^G	0.0044
tEC	0.0053	Tok	0.0031	tog	0.0043
Tit	0.0051	ved	0.0041	t@v	0.0049
vEk	0.0057	zId	0.0049	vad	0.0029
Mean	**0.004408**	**Mean**	**0.00452**	**Mean**	**0.0041**

List 10		**List 11**		**List 12**	
Klattese	Biphone sum	Klattese	Biphone sum	Klattese	Biphone Sum
bem	0.0058	beT	0.0032	bog	0.0049
C^t	0.0046	Cas	0.0032	Cab	0.0052
CEg	0.0032	Dep	0.0031	deD	0.0031
DId	0.0049	deb	0.0054	daD	0.0057
dav	0.0052	faD	0.004	DIf	0.0034
deS	0.0033	f^v	0.0037	fut	0.0029
fEf	0.0044	gIC	0.0038	f@T	0.0047
git	0.0051	hem	0.0042	g^C	0.0036
hib	0.003	Jid	0.0056	gip	0.0033
hEC	0.0054	J^f	0.0041	hEb	0.006
Jis	0.0038	kEm	0.0045	Jom	0.0031
Jam	0.0049	mif	0.0059	JEZ	0.0031
moT	0.0037	mup	0.0038	moC	0.0036
nEJ	0.0029	n@z	0.0029	meT	0.0039
nup	0.0038	pig	0.0045	niS	0.0029
noS	0.0035	poT	0.0044	nEv	0.0053
pif	0.0046	SEb	0.0032	pEJ	0.0052
SiC	0.0032	S@T	0.0035	p^v	0.0048
seD	0.0033	siC	0.0056	sog	0.0043
toJ	0.0035	tof	0.0036	Sup	0.0033
T@G	0.0051	T@g	0.0037	SIS	0.0052
tIv	0.0053	tEZ	0.0052	t@f	0.0051
tib	0.0044	tIJ	0.0035	t^T	0.0034
vIz	0.0057	von	0.0042	TIv	0.0035
zid	0.0043	zok	0.0031	v@z	0.0031
Mean	**0.004276**	**Mean**	**0.004076**	**Mean**	**0.004104**

List 13		**List 14**		**List 15**	
Klattese	Biphone sum	Klattese	Biphone sum	Klattese	Biphone sum
Con	0.0043	bib	0.0051	beS	0.0034
Dok	0.0036	CEp	0.0035	C^s	0.0045
div	0.0035	Cet	0.0039	DIt	0.0059
dED	0.0051	DEf	0.0032	d^D	0.0058
fav	0.0035	dEG	0.0043	fig	0.003
gom	0.0045	duv	0.0035	fik	0.0045
gud	0.0032	fup	0.0031	gaJ	0.0046
hik	0.0042	foC	0.0056	gEv	0.0044
haz	0.0048	ged	0.0048	hev	0.0051
JEJ	0.0036	gas	0.0054	J^k	0.0053
Jot	0.0052	h^J	0.0048	JEz	0.0031
kUt	0.0034	hEZ	0.0053	keb	0.0052
mEZ	0.0051	JED	0.0039	n@f	0.0036
niC	0.0041	JIv	0.004	nam	0.005
n^z	0.0041	kEb	0.0035	pEb	0.0054
piT	0.0043	meC	0.0038	piD	0.0041
SIb	0.0031	mis	0.005	peC	0.0033
sof	0.0036	nim	0.0036	SIT	0.003
SEg	0.0038	p^S	0.0041	sug	0.0033
SEp	0.0041	SUt	0.003	S^p	0.0035
tIC	0.0055	seT	0.0033	Ton	0.0042
TIC	0.0037	tig	0.0041	t^J	0.0033
t@S	0.0042	tiv	0.005	tEJ	0.0057
veb	0.0031	T^z	0.0036	vIC	0.0032
z@d	0.0048	vet	0.0036	zos	0.0035
Mean	**0.004096**	**Mean**	**0.00412**	**Mean**	**0.004236**

List 16		**List 17**		**List 18**	
Klattese	Biphone sum	Klattese	Biphone sum	Klattese	Biphone Sum
bef	0.0038	biZ	0.0042	bop	0.0054
C@b	0.0037	C^G	0.0042	Cev	0.0046
Cis	0.0035	Cut	0.0034	d@J	0.0048
DIz	0.0053	d@D	0.0047	Don	0.0047
duT	0.0031	doT	0.003	faS	0.0037
dis	0.0041	DIp	0.0054	fET	0.0034
f^C	0.0035	feb	0.0042	g^z	0.0047
f@D	0.0033	g@v	0.0036	hEz	0.0053
gog	0.0039	haD	0.0052	JIC	0.0042
huv	0.003	haf	0.0049	J^v	0.0037
Jem	0.0045	Jop	0.003	kis	0.0033
kIb	0.0059	Jiv	0.0032	mEb	0.0058
mip	0.0058	moJ	0.0035	meS	0.0041
nIT	0.0037	miT	0.0033	noC	0.0034
nap	0.0051	nEg	0.0037	nEp	0.004
poS	0.0044	peb	0.0057	pod	0.0058
suk	0.0036	piS	0.0042	Sam	0.006
S^d	0.003	SED	0.0033	SIf	0.0048
SaG	0.0032	soC	0.0036	soS	0.0037
Tot	0.0038	sum	0.0044	suv	0.0045
tIT	0.0043	Sis	0.0038	tET	0.0054
tov	0.004	S^z	0.0035	TEt	0.0056
taJ	0.0033	T^s	0.0047	tuv	0.0048
v@C	0.0039	tiS	0.0038	vat	0.0059
zot	0.0038	vek	0.0058	z@G	0.0045
Mean	**0.00398**	**Mean**	**0.004092**	**Mean**	**0.004644**

List 19		**List 20**		**List 21**	
Klattese	Biphone sum	Klattese	Biphone sum	Klattese	Biphone sum
big	0.0048	beC	0.0031	CIv	0.0046
CIb	0.0037	Cid	0.0053	Cˆp	0.0034
D@p	0.0056	C@g	0.0045	dˆJ	0.0056
dˆT	0.0057	dof	0.0029	D@G	0.0057
Dos	0.004	dEZ	0.0043	fEb	0.0039
foS	0.0057	f@f	0.0047	fEg	0.0045
faG	0.004	fun	0.0037	gEm	0.0032
g@T	0.0038	gut	0.0032	gaf	0.0044
goT	0.0033	hoC	0.0043	hoS	0.0044
hoJ	0.0042	has	0.0059	JiC	0.0032
J@f	0.0043	Jˆb	0.0055	JET	0.0033
Jet	0.0047	J@T	0.0043	kez	0.0034
mED	0.0059	kIJ	0.005	mep	0.0055
mim	0.0039	moS	0.0037	nof	0.0034
nˆd	0.0036	nib	0.0035	pEZ	0.0047
nik	0.0047	niv	0.0041	pˆz	0.0057
pˆC	0.0046	pˆD	0.0036	SEv	0.0054
pep	0.005	peS	0.0036	Seb	0.0041
sub	0.0037	Sok	0.0043	soT	0.0037
Sˆg	0.0032	Som	0.0029	T@d	0.0054
t@D	0.0037	seb	0.0056	TIg	0.0055
tef	0.0033	T@p	0.005	tis	0.0056
TIS	0.0047	TEv	0.0033	tEz	0.0052
vIv	0.003	tˆz	0.0056	tuC	0.004
zIS	0.0038	vam	0.0041	vok	0.0031
Mean	**0.004276**	**Mean**	**0.00424**	**Mean**	**0.004436**

List 22		**List 23**		**List 24**	
Klattese	Biphone sum	Klattese	Biphone sum	Klattese	Biphone Sum
bov	0.0046	bof	0.0031	CIf	0.0054
Cad	0.0041	Civ	0.0029	C@v	0.0031
C@C	0.0034	dEC	0.0044	DEg	0.0033
Deb	0.0038	DEv	0.0049	dEg	0.0056
dob	0.0039	foJ	0.0055	dod	0.0044
fˆg	0.0043	fim	0.0034	faJ	0.0039
faz	0.0036	gof	0.0032	fˆp	0.0046
goJ	0.0031	gˆg	0.0044	gId	0.0059
gok	0.0059	heb	0.0039	gav	0.0042
him	0.0031	hun	0.0046	hob	0.0053
Jˆp	0.0046	JEC	0.0032	JIS	0.0052
keS	0.0031	J@S	0.0034	J@D	0.0029
mom	0.0049	kik	0.0033	kus	0.0029
nˆv	0.0032	meD	0.0039	mEC	0.0052
n@T	0.0036	miZ	0.0029	mef	0.0045
pUk	0.005	noT	0.0035	nˆG	0.0049
sib	0.005	pog	0.005	nas	0.0029
Saf	0.0029	pim	0.0049	peT	0.0034
Sˆs	0.0046	seC	0.0032	SˆG	0.0043
siT	0.0045	Sˆf	0.003	sez	0.0038
tED	0.006	S@p	0.006	toC	0.0036
tif	0.0042	TIf	0.0043	teJ	0.0031
Tip	0.0033	tus	0.005	Tˆb	0.0045
Tos	0.0035	toT	0.0037	vIS	0.0042
vev	0.0043	vab	0.004	zIz	0.0053
Mean	**0.0041**	**Mean**	**0.003984**	**Mean**	**0.004256**

List 25		**List 26**		**List 27**	
Klattese	Biphone sum	Klattese	Biphone sum	Klattese	Biphone Sum
biD	0.0044	CEv	0.0048	biT	0.0046
C^z	0.0034	dEJ	0.0048	Cot	0.0039
Ced	0.0044	dut	0.0043	Cos	0.0036
Dip	0.0034	Did	0.0044	D@f	0.0031
dog	0.0036	DIg	0.0046	daS	0.0054
dUk	0.0033	f^S	0.003	d@v	0.0059
f@v	0.0045	fEZ	0.0032	faf	0.0037
fov	0.006	guz	0.0034	f^t	0.0058
goC	0.0032	gaz	0.0043	gUt	0.0034
hes	0.0054	h^T	0.0049	hoT	0.0044
J^S	0.003	haS	0.0049	Jad	0.0037
kEf	0.004	Jup	0.0038	Jap	0.005
mib	0.0038	JEv	0.006	kEv	0.0057
meZ	0.0038	kef	0.0035	mEz	0.0051
nIf	0.0055	mUk	0.0032	n^k	0.0048
n^C	0.003	nef	0.0029	neb	0.0046
pob	0.0053	peD	0.0034	pED	0.0055
p^T	0.0035	pov	0.0047	S@b	0.0039
SEJ	0.003	suC	0.0037	SIC	0.0042
som	0.0049	Sag	0.0031	siS	0.0044
ted	0.006	tEb	0.0059	Tin	0.0044
t@J	0.0038	teb	0.005	tug	0.0036
T^t	0.0048	T^p	0.0036	t@T	0.0051
vap	0.0042	vIg	0.005	tup	0.0058
zit	0.0051	zin	0.0044	voz	0.003
Mean	**0.004212**	**Mean**	**0.004192**	**Mean**	**0.004504**

APPENDIX C – Proportion Correct Phoneme Data by Filter Condition and Age Group

Full bandwidth conditions

FB	Young	Old	Adult
b	0.35	0.45	0.52
C	0.88	0.92	0.95
D	0.45	0.43	0.56
d	0.83	0.88	0.88
f	0.60	0.66	0.70
G	0.53	0.43	0.53
g	0.74	0.78	0.88
h	0.33	0.25	0.26
J	0.92	0.89	0.96
k	0.81	0.85	0.91
m	0.53	0.61	0.78
n	0.64	0.73	0.75
p	0.52	0.55	0.70
S	0.81	0.82	0.86
s	0.83	0.91	0.95
t	0.93	0.96	0.98
T	0.47	0.49	0.51
v	0.55	0.68	0.71
Z	0.60	0.78	0.78
z	0.88	0.90	0.87

Low-pass conditions

LP1	Young	Old	Adult
b	0.30	0.42	0.44
C	0.84	0.88	0.94
D	0.33	0.34	0.38
d	0.78	0.84	0.86
f	0.52	0.58	0.61
G	0.43	0.44	0.59
g	0.71	0.82	0.86
h	0.23	0.23	0.39
J	0.87	0.88	0.90
k	0.82	0.87	0.90
m	0.56	0.57	0.68
n	0.62	0.68	0.85
p	0.43	0.46	0.54
S	0.72	0.76	0.85
s	0.75	0.81	0.87
t	0.91	0.93	0.92
T	0.31	0.32	0.26
v	0.54	0.60	0.61
Z	0.69	0.84	0.84
z	0.71	0.81	0.76

LP2	Young	Old	Adult
b	0.27	0.41	0.42
C	0.59	0.60	0.64
D	0.39	0.26	0.26
d	0.40	0.40	0.51
f	0.45	0.49	0.53
G	0.35	0.54	0.73
g	0.65	0.76	0.83
h	0.20	0.17	0.26
J	0.55	0.57	0.50
k	0.69	0.71	0.80
m	0.43	0.50	0.61
n	0.58	0.54	0.70
p	0.39	0.47	0.65
S	0.62	0.68	0.79
s	0.14	0.10	0.06
t	0.33	0.35	0.41
T	0.24	0.27	0.31
v	0.45	0.60	0.56
Z	0.46	0.63	0.45
z	0.17	0.15	0.16

LP3	Young	Old	Adult
b	0.16	0.30	0.35
C	0.06	0.05	0.05
D	0.11	0.12	0.09
d	0.18	0.15	0.18
f	0.31	0.34	0.29
G	0.13	0.15	0.32
g	0.30	0.32	0.44
h	0.18	0.21	0.15
J	0.04	0.04	0.08
k	0.14	0.22	0.31
m	0.34	0.47	0.50
n	0.28	0.32	0.30
p	0.21	0.29	0.26
S	0.03	0.03	0.03
s	0.04	0.03	0.06
t	0.20	0.18	0.12
T	0.14	0.10	0.24
v	0.28	0.36	0.40
Z	0.04	0.01	0.00
z	0.07	0.06	0.15

High-pass conditions

HP1	Young	Old	Adult
b	0.39	0.48	0.53
C	0.85	0.90	0.97
D	0.44	0.39	0.42
d	0.80	0.90	0.95
f	0.57	0.65	0.61
G	0.40	0.41	0.52
g	0.79	0.86	0.94
h	0.31	0.35	0.23
J	0.89	0.88	0.88
k	0.79	0.94	0.96
m	0.50	0.53	0.65
n	0.51	0.56	0.67
p	0.45	0.59	0.66
S	0.79	0.87	0.91
s	0.83	0.93	0.97
t	0.94	0.96	0.94
T	0.43	0.45	0.49
v	0.57	0.68	0.70
Z	0.67	0.85	0.71
z	0.87	0.93	0.94

HP2	Young	Old	Adult
b	0.44	0.57	0.66
C	0.82	0.87	0.94
D	0.38	0.32	0.26
d	0.87	0.90	0.86
f	0.55	0.63	0.69
G	0.29	0.44	0.42
g	0.82	0.89	0.91
h	0.32	0.51	0.50
J	0.81	0.82	0.86
k	0.85	0.89	0.99
m	0.52	0.57	0.63
n	0.71	0.77	0.88
p	0.64	0.71	0.81
S	0.77	0.86	0.85
s	0.81	0.88	0.83
t	0.93	0.94	0.91
T	0.30	0.29	0.31
v	0.65	0.72	0.78
Z	0.73	0.83	0.68
z	0.86	0.90	1.00

HP3	Young	Old	Adult
b	0.52	0.60	0.61
C	0.72	0.78	0.81
D	0.41	0.41	0.32
d	0.87	0.88	0.93
f	0.70	0.79	0.76
G	0.27	0.34	0.38
g	0.70	0.78	0.75
h	0.31	0.36	0.50
J	0.76	0.86	0.84
k	0.82	0.83	0.83
m	0.48	0.52	0.62
n	0.64	0.76	0.82
p	0.64	0.67	0.76
S	0.80	0.84	0.90
s	0.75	0.88	0.91
t	0.83	0.90	0.96
T	0.29	0.32	0.36
v	0.64	0.77	0.89
Z	0.70	0.89	0.90
z	0.84	0.91	0.96

APPENDIX D- Confusion matrices for phoneme scoring – Adults

FB

	b	C	D	d	f	G	g	h	J	k	m	n	p	S	s	t	T	v	Z	z
b	49	0	3	1	4	0	2	1	0	0	1	0	3	0	0	0	7	5	0	0
C	0	113	0	0	0	0	0	0	1	0	0	0	0	10	0	0	1	0	0	0
D	0	0	39	2	0	0	0	0	0	0	0	0	0	0	0	0	8	2	0	2
d	7	1	4	79	2	1	2	0	0	0	1	4	0	0	0	0	1	6	1	3
f	0	0	0	0	95	0	0	0	0	0	3	0	6	0	0	0	14	6	0	0
G	0	0	0	0	0	8	0	0	0	0	3	1	0	0	0	0	0	1	0	0
g	4	0	4	1	0	1	94	1	2	0	0	0	1	1	0	0	0	3	0	0
h	0	0	0	0	3	0	0	12	0	0	0	0	2	0	0	0	0	0	0	0
J	0	4	1	1	6	0	0	0	100	0	0	0	0	3	0	0	0	0	3	1
k	0	0	0	0	1	0	2	12	0	43	0	2	8	0	0	2	1	0	0	0
m	1	0	1	0	0	2	0	0	0	0	73	8	0	0	0	0	0	2	0	0
n	1	0	6	3	0	2	0	1	0	0	8	62	0	0	0	0	0	0	0	0
p	3	0	2	1	4	0	0	14	0	0	1	1	71	0	0	0	2	1	0	0
S	0	0	0	0	1	0	0	0	0	0	0	0	0	101	1	0	0	0	0	0
s	0	0	0	0	3	0	0	0	0	0	0	0	0	0	60	0	3	0	0	1
t	0	1	1	0	3	0	0	1	0	4	0	0	8	0	0	105	4	0	0	0
T	0	0	0	0	5	0	0	0	0	0	0	0	1	0	0	0	49	0	0	0
V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
v	25	0	5	0	5	0	4	0	0	0	4	0	1	0	0	0	2	82	0	0
Z	0	0	1	0	0	0	0	0	1	0	0	0	0	2	1	0	3	1	21	0
z	1	0	1	2	0	0	1	0	0	0	0	1	0	0	1	0	1	5	2	54
X	3	0	2	0	4	1	2	5	0	0	0	4	0	0	0	0	1	1	0	1
%	0.52	0.95	0.56	0.88	0.70	0.53	0.88	0.26	0.96	0.91	0.78	0.75	0.70	0.86	0.95	0.98	0.51	0.71	0.78	0.87

LP1

	b	C	D	d	f	G	g	h	J	k	m	n	p	S	s	t	T	v	Z	z
b	44	0	3	0	10	0	0	0	0	0	0	0	1	0	0	0	7	8	0	0
C	0	119	0	0	1	0	0	1	2	0	0	0	0	9	0	3	3	0	0	0
D	0	0	30	0	1	0	0	1	0	0	0	0	0	0	0	0	3	3	0	0
d	4	0	5	92	1	0	3	0	0	0	3	1	0	0	0	0	1	2	0	3
f	1	0	1	0	76	0	0	0	0	0	2	0	9	0	1	1	28	6	0	1
G	0	0	0	0	0	10	0	0	0	0	4	1	0	0	0	0	0	1	0	0
g	4	0	3	8	0	0	66	1	2	0	1	1	1	0	0	0	0	6	0	1
h	0	0	0	0	0	0	0	16	0	0	0	0	4	0	0	1	0	0	0	0
J	0	2	0	0	1	0	0	0	95	1	0	0	0	0	0	0	0	3	1	0
k	1	0	0	0	7	0	0	3	1	52	0	1	15	0	0	1	1	0	0	0
m	1	0	1	0	0	0	0	1	0	0	61	6	1	0	0	0	0	0	0	0
n	0	0	1	0	0	4	0	0	0	1	11	66	2	0	0	0	0	2	0	0
p	0	0	0	0	3	0	1	14	0	0	1	0	57	0	0	0	2	1	0	0
S	1	2	0	1	2	0	0	0	0	0	1	0	1	88	1	0	2	0	1	0
s	0	0	0	0	10	0	0	0	0	0	0	0	1	3	72	3	4	0	0	2
t	0	1	0	0	3	0	3	0	0	4	0	0	11	0	0	109	2	1	0	0
T	0	0	2	0	0	0	0	0	0	0	0	0	1	0	6	0	24	2	0	0
V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
v	32	1	23	3	8	2	2	0	0	0	3	2	0	0	1	0	6	62	0	5
Z	0	0	0	0	0	0	0	0	6	0	0	0	0	3	0	0	0	0	16	0
z	4	0	8	0	0	1	0	0	0	0	0	0	0	0	2	0	0	4	1	52
X	8	1	2	3	2	0	2	4	0	0	3	0	2	0	0	0	11	1	0	4
%	0.44	0.94	0.38	0.86	0.61	0.59	0.86	0.39	0.90	0.90	0.68	0.85	0.54	0.85	0.87	0.92	0.26	0.61	0.84	0.76

LP2

	b	C	D	d	f	G	g	h	J	k	m	n	p	S	s	t	T	v	Z	z
b	42	0	5	4	9	0	2	2	0	0	6	3	0	1	0	1	7	4	0	1
C	0	68	0	0	1	0	0	0	3	0	0	0	0	9	1	4	0	0	0	0
D	0	0	21	3	0	0	0	0	0	0	0	0	0	1	2	0	2	3	0	6
d	3	0	4	47	0	0	3	0	11	0	0	4	0	1	6	0	1	2	1	3
f	7	0	2	2	70	0	0	2	1	1	3	1	2	1	27	0	24	4	0	3
G	0	0	0	0	0	16	0	0	0	0	6	1	0	0	3	0	0	0	0	0
g	5	1	7	17	1	1	79	1	11	0	2	0	0	0	1	1	3	6	0	9
h	0	1	0	0	0	0	0	11	0	1	0	0	5	2	2	1	0	0	0	0
J	1	0	2	0	2	0	2	0	51	0	0	0	0	1	0	0	1	3	7	2
k	0	7	0	1	4	0	3	2	0	35	0	0	15	0	8	29	4	0	0	2
m	1	0	2	3	0	0	0	0	1	0	60	4	0	0	0	0	0	3	0	0
n	1	0	3	0	0	0	2	0	0	0	11	54	0	0	1	0	0	1	0	4
p	1	7	0	0	12	0	0	23	7	3	1	1	66	0	9	21	7	3	0	0
S	0	8	0	2	2	0	1	0	1	0	0	0	0	85	2	1	1	0	0	0
s	1	0	0	1	6	0	0	0	0	0	0	0	0	0	5	0	6	0	0	1
t	2	13	0	0	1	2	0	0	2	3	2	2	12	0	0	46	6	2	0	0
T	1	0	1	1	4	0	0	1	1	0	0	0	0	0	4	1	31	0	0	1
V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
v	27	0	14	6	6	1	2	0	3	0	6	1	1	2	3	0	3	64	3	16
Z	0	0	1	0	1	0	0	0	6	0	0	0	0	0	0	0	0	3	10	1
z	1	0	9	0	2	0	0	0	0	0	1	0	0	0	0	0	2	6	1	11
X	7	2	9	5	11	2	1	0	5	1	1	6	1	4	5	6	3	9	0	9
%	0.42	0.64	0.26	0.51	0.53	0.73	0.83	0.26	0.50	0.80	0.61	0.70	0.65	0.79	0.06	0.41	0.31	0.56	0.45	0.16

LP3

	b	C	D	d	f	G	g	h	J	k	m	n	p	S	s	t	T	v	Z	z
b	33	2	14	12	14	1	4	1	7	0	3	1	3	6	7	4	6	6	3	3
C	0	6	0	1	0	0	0	0	1	0	0	0	8	3	4	0	0	0	0	0
D	0	0	7	1	0	0	0	0	3	2	0	1	0	1	1	3	2	1	0	1
d	5	2	2	19	1	1	8	1	14	0	2	1	1	6	5	0	1	4	1	3
f	2	16	3	5	37	0	10	8	0	6	0	0	5	30	13	10	15	1	0	0
G	0	0	1	0	0	7	0	0	0	0	8	3	0	0	0	1	0	0	0	0
g	16	1	11	26	3	5	47	2	30	0	2	0	2	5	7	2	2	6	4	9
h	0	1	0	1	0	0	0	6	2	1	0	1	4	0	0	4	1	1	0	0
J	1	0	2	1	1	0	2	0	9	0	0	0	0	1	1	1	0	1	0	1
k	3	13	0	4	8	0	2	4	1	19	0	1	22	7	1	10	3	0	0	0
m	4	0	5	6	0	1	4	0	3	0	43	24	5	0	0	0	1	4	2	1
n	0	0	1	0	0	3	3	0	1	1	13	24	1	0	0	2	0	1	1	1
p	5	18	2	1	24	0	0	8	3	16	0	2	31	6	4	33	11	2	2	2
S	0	1	0	0	3	0	0	0	0	1	1	0	1	3	2	1	1	0	1	0
s	1	3	0	0	2	0	0	1	0	0	0	0	0	5	5	1	1	1	0	0
t	5	24	1	3	7	0	1	5	0	6	1	1	23	9	7	12	8	1	0	0
T	1	3	1	1	3	0	0	0	0	0	0	0	0	3	5	1	20	0	0	0
V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
v	9	2	10	8	6	1	6	0	6	1	4	5	4	8	12	4	6	40	7	9
Z	0	0	1	2	0	0	0	0	1	0	1	0	2	0	0	0	0	1	0	0
z	1	1	4	2	0	1	1	0	1	1	0	0	0	1	0	0	0	5	1	7
X	9	22	14	13	20	2	19	5	36	7	8	17	6	10	6	12	6	25	2	10
%	0.35	0.05	0.09	0.18	0.29	0.32	0.44	0.15	0.08	0.31	0.50	0.30	0.26	0.03	0.06	0.12	0.24	0.40	0.00	0.15

HP1

	b	C	D	d	f	G	g	h	J	k	m	n	p	S	s	t	T	v	Z	z
b	50	0	1	1	19	1	1	0	0	0	4	0	2	0	0	2	3	2	0	0
C	0	99	0	0	0	0	0	0	5	0	0	0	0	3	0	0	0	0	0	0
D	0	0	34	1	1	0	0	0	0	0	1	2	0	0	0	0	4	4	0	0
d	3	0	7	89	1	1	2	0	0	0	0	3	0	0	0	1	2	1	0	1
f	0	0	3	0	86	0	0	2	0	0	3	0	7	0	0	0	14	2	0	0
G	0	0	0	1	0	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0
g	3	0	1	0	2	4	100	1	2	0	1	0	3	0	0	0	1	2	0	0
h	0	0	0	0	0	0	0	9	0	0	0	0	3	0	0	0	1	0	0	0
J	0	1	3	0	0	0	0	0	98	0	0	0	0	1	0	0	0	0	7	0
k	1	0	0	0	0	0	0	5	0	53	0	3	6	0	0	2	1	0	0	0
m	0	0	1	0	2	1	0	0	0	0	55	5	0	0	0	0	1	0	0	0
n	0	0	3	1	0	1	0	0	0	0	7	52	1	0	0	0	0	3	0	0
p	1	0	0	0	6	0	0	18	1	0	2	1	69	0	0	1	4	0	0	0
S	0	0	0	0	0	0	0	0	0	0	0	0	0	89	2	0	1	0	0	0
s	0	0	0	0	3	0	0	0	0	0	0	0	0	1	70	0	3	0	0	0
t	0	2	1	0	1	0	0	1	0	1	0	0	9	0	0	103	2	0	0	0
T	0	0	1	0	2	1	0	0	0	0	0	0	0	0	0	0	48	0	0	0
V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0
v	28	0	18	1	10	0	2	0	0	0	5	10	0	0	0	0	5	74	0	1
Z	0	0	1	0	0	0	0	0	2	0	0	0	0	2	0	0	0	0	17	1
z	0	0	4	0	1	0	0	0	0	0	0	0	0	0	0	0	0	8	0	72
X	9	0	3	0	7	1	1	3	4	1	6	2	4	2	0	0	8	6	0	2
%	0.53	0.97	0.42	0.95	0.61	0.52	0.94	0.23	0.88	0.96	0.65	0.67	0.66	0.91	0.97	0.94	0.49	0.70	0.71	0.94

HP2

	b	C	D	d	f	G	g	h	J	k	m	n	p	S	s	t	T	v	Z	z
b	61	0	3	0	5	0	0	0	0	0	6	0	1	0	1	0	2	1	0	0
C	0	112	0	0	0	0	0	0	8	0	0	0	0	5	0	0	0	0	0	0
D	1	0	20	0	0	0	1	0	0	0	0	0	0	0	0	0	6	2	0	0
d	1	0	9	76	1	1	1	0	0	0	0	1	0	0	0	0	4	0	0	0
f	1	0	0	0	87	3	0	0	0	0	4	1	7	0	0	0	19	3	0	0
G	0	0	2	1	0	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0
g	5	0	0	3	1	2	88	0	0	0	4	2	0	0	0	0	0	0	0	0
h	0	0	0	0	0	0	0	23	0	0	0	0	1	0	0	0	0	0	0	0
J	0	1	0	0	0	0	0	0	96	0	0	0	0	4	0	0	0	0	1	0
k	0	0	0	0	0	0	2	5	0	67	0	0	6	0	0	0	0	0	0	0
m	3	0	2	0	0	0	0	0	0	0	56	2	0	0	0	3	3	1	0	0
n	1	0	8	6	1	1	0	1	0	0	3	66	0	0	0	0	2	0	0	0
p	1	0	0	0	1	0	0	15	0	0	0	0	88	0	0	4	0	0	0	0
S	0	0	0	0	1	0	0	0	1	0	4	0	0	93	2	0	1	0	1	0
s	0	0	1	0	1	0	0	0	0	0	0	0	0	3	68	0	7	0	0	0
t	0	2	0	0	1	0	0	1	3	0	0	0	4	0	0	94	4	0	0	0
T	0	0	1	1	2	0	0	0	0	0	0	0	0	0	0	0	30	0	0	0
V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
v	19	0	20	1	13	4	2	0	0	0	6	3	0	0	0	0	6	76	4	0
Z	0	0	0	0	0	0	0	0	2	0	0	0	0	3	0	0	0	5	17	0
z	0	0	6	0	4	0	0	0	1	0	0	0	0	0	5	0	3	6	2	57
X	0	4	5	0	9	0	3	1	1	1	6	0	2	2	6	2	9	4	0	0
%	0.66	0.94	0.26	0.86	0.69	0.42	0.91	0.50	0.86	0.99	0.63	0.88	0.81	0.85	0.83	0.91	0.31	0.78	0.68	1.00

HP3

	b	C	D	d	f	G	g	h	J	k	m	n	p	S	s	t	T	v	Z	z
b	62	0	1	0	1	0	10	1	0	0	9	3	9	0	0	0	2	1	0	0
C	0	89	1	0	0	0	0	0	9	1	0	0	0	6	0	0	0	0	0	0
D	0	0	27	0	2	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0
d	0	0	3	91	0	0	2	1	2	0	2	1	0	0	0	0	1	1	0	0
f	2	0	3	0	95	0	1	0	1	0	0	0	5	0	0	0	18	4	0	0
G	0	0	0	0	0	9	0	0	0	0	2	0	0	0	0	0	0	0	0	0
g	1	0	0	1	1	6	69	1	0	1	0	0	2	1	0	0	0	0	0	0
h	0	0	0	1	0	0	1	21	0	0	0	0	1	0	0	0	0	0	0	0
J	0	16	0	1	0	1	0	0	89	0	0	0	0	0	0	0	0	0	1	0
k	0	0	0	0	0	0	2	3	2	48	0	0	1	0	1	0	0	0	0	0
m	1	0	1	0	0	0	1	1	0	0	56	4	0	0	0	0	0	0	0	0
n	0	0	2	0	0	2	0	0	0	0	3	62	0	0	0	0	0	0	0	0
p	5	0	0	0	0	1	2	12	0	1	1	0	84	0	0	2	0	1	0	0
S	1	2	0	0	1	0	0	0	0	0	1	0	1	102	1	0	0	1	0	0
s	0	0	1	0	2	0	0	0	0	0	0	0	0	1	83	0	10	0	0	0
t	0	1	0	0	0	0	1	0	1	0	0	0	0	0	0	102	1	0	0	0
T	0	0	2	0	5	0	0	0	0	0	0	0	0	0	0	0	36	3	0	0
V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
v	26	0	30	4	18	3	1	0	0	2	16	4	2	0	0	1	13	88	1	0
Z	0	0	0	0	0	0	0	0	2	0	0	0	0	3	0	0	0	0	19	2
z	0	0	9	0	0	0	0	0	0	0	0	0	0	0	6	0	7	0	0	46
X	4	2	5	0	0	2	2	2	0	5	0	2	6	0	0	1	8	0	0	0
%	0.61	0.81	0.32	0.93	0.76	0.38	0.75	0.50	0.84	0.83	0.62	0.82	0.76	0.90	0.91	0.96	0.36	0.89	0.90	0.96

APPENDIX E - Confusion matrices for phoneme scoring – Older Children

FB

	b	C	D	d	f	G	g	h	J	k	m	n	p	S	s	t	T	v	Z	z
b	152	0	7	5	30	0	7	5	1	0	10	3	4	0	1	1	17	14	0	0
C	2	377	1	0	3	0	0	1	7	1	0	0	2	37	1	1	1	0	0	0
D	9	0	119	2	8	0	1	0	0	0	7	4	2	0	0	0	4	10	1	2
d	16	0	14	293	2	0	14	1	6	0	1	3	1	1	1	0	0	14	1	6
f	15	2	7	1	278	1	6	4	2	2	3	2	27	2	0	1	48	9	0	0
G	0	0	2	1	0	29	3	0	0	0	3	0	0	0	0	0	0	1	0	0
g	14	0	12	6	1	10	267	4	3	1	1	0	3	1	0	0	4	13	0	0
h	2	0	2	0	3	0	2	39	1	1	0	0	18	0	1	0	1	2	0	0
J	2	12	2	1	3	0	2	1	325	1	1	1	1	5	1	0	2	7	7	1
k	2	2	1	0	8	1	9	17	1	161	5	2	28	0	0	1	4	0	0	0
m	2	0	3	1	0	5	1	2	0	0	190	22	2	0	0	0	0	4	0	0
n	5	0	6	3	1	12	1	0	0	2	42	196	4	1	0	1	0	3	1	0
p	8	2	4	0	13	0	0	57	3	7	3	6	210	0	0	1	9	3	0	0
S	0	3	1	0	1	0	0	0	0	0	1	0	3	318	3	0	3	0	1	0
s	1	0	0	0	8	0	0	1	0	0	0	0	2	7	244	2	23	0	0	8
t	2	4	2	6	8	0	1	8	2	11	2	3	37	2	1	387	11	0	0	0
T	1	0	3	0	13	0	2	0	1	0	0	0	8	1	3	1	168	3	0	0
V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
v	87	0	54	11	30	2	17	0	0	1	24	12	9	0	2	2	13	253	3	1
Z	2	1	5	1	2	0	1	0	5	0	0	1	0	11	0	0	2	2	56	2
z	2	0	16	1	0	1	1	0	2	0	3	0	2	1	7	1	4	10	2	177
X	16	7	13	2	11	7	9	14	5	2	15	15	17	2	2	4	26	22	0	0
%	0.45	0.92	0.43	0.88	0.66	0.43	0.78	0.25	0.89	0.85	0.61	0.73	0.55	0.82	0.91	0.96	0.49	0.68	0.78	0.90

LP1

	b	C	D	d	f	G	g	h	J	k	m	n	p	S	s	t	T	v	Z	z
b	146	0	15	2	31	1	7	1	0	0	12	7	6	0	1	1	19	23	0	0
C	0	347	2	0	2	0	0	0	9	0	0	2	3	49	1	5	1	1	0	2
D	5	0	94	4	7	0	3	0	0	0	0	7	2	0	1	2	12	12	0	2
d	18	1	27	279	6	3	12	1	9	0	4	5	2	1	5	3	14	7	0	3
f	17	2	1	0	262	0	1	7	1	2	6	1	44	1	8	1	82	15	0	0
G	0	0	0	1	0	35	1	0	0	0	3	0	0	0	0	0	0	0	1	0
g	12	0	7	6	3	3	274	5	6	2	3	2	4	0	0	0	4	16	0	0
h	0	0	0	0	0	0	2	33	0	1	0	2	14	0	0	2	1	1	0	0
J	2	20	5	2	1	0	3	0	328	0	0	0	0	12	0	0	2	2	4	1
k	2	1	0	0	13	0	7	13	1	166	1	0	47	0	0	5	7	1	0	0
m	6	0	4	1	3	11	1	0	0	0	178	34	1	0	0	0	1	6	2	0
n	0	0	4	5	2	14	2	0	0	0	54	177	4	0	0	0	1	6	0	0
p	14	1	0	2	25	0	0	62	1	4	3	1	178	0	0	0	11	4	0	0
S	0	5	0	0	3	1	0	0	0	0	0	0	0	285	9	0	2	0	0	0
s	0	0	0	2	8	0	0	0	0	1	0	0	1	8	230	1	12	1	0	9
t	1	10	1	5	9	0	2	7	0	11	2	2	47	1	3	352	19	2	0	0
T	2	0	8	0	18	1	0	0	0	0	0	1	5	0	5	1	114	3	0	0
V	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
v	101	2	71	8	32	4	14	1	2	1	32	11	10	0	2	0	21	211	2	13
Z	3	1	9	5	1	1	0	0	14	0	0	0	1	18	0	0	2	7	62	4
z	4	0	15	4	3	0	0	1	0	0	0	1	0	0	13	1	6	17	2	160
X	14	3	17	5	25	5	5	10	2	2	17	8	14	1	6	4	26	12	1	4
%	0.42	0.88	0.34	0.84	0.58	0.44	0.82	0.23	0.88	0.87	0.57	0.68	0.46	0.76	0.81	0.93	0.32	0.60	0.84	0.81

LP2

	b	C	D	d	f	G	g	h	J	k	m	n	p	S	s	t	T	v	Z	z
b	131	1	21	31	44	0	11	9	4	2	12	11	5	3	16	6	18	16	2	4
C	0	236	0	0	7	1	0	1	15	0	0	0	3	48	4	34	2	0	0	1
D	10	2	68	10	5	3	1	0	5	1	0	2	1	1	8	0	9	27	0	11
d	19	3	20	139	4	1	13	1	16	1	3	5	3	3	10	5	6	11	2	16
f	9	9	10	7	219	0	3	8	4	4	6	5	35	7	74	15	63	11	1	5
G	1	0	0	0	0	44	1	0	0	0	5	0	0	0	1	0	0	0	0	0
g	19	2	8	52	5	3	276	0	31	4	2	3	5	0	8	8	2	4	2	8
h	1	8	2	2	1	0	1	25	1	5	3	2	14	3	2	21	4	1	0	0
J	0	10	4	19	2	0	5	1	221	0	3	0	2	15	1	1	4	4	6	7
k	2	37	2	0	12	0	5	12	6	132	3	4	32	4	9	50	8	2	0	0
m	6	1	3	3	5	5	2	0	2	0	149	43	1	1	1	1	2	7	0	2
n	7	0	7	8	0	10	2	0	0	2	56	142	2	0	3	0	7	6	1	4
p	12	17	4	2	27	0	3	52	6	14	4	8	179	2	7	86	15	2	0	3
S	0	22	1	3	9	0	0	0	3	0	1	0	4	252	13	3	10	1	2	1
s	1	1	0	0	7	0	0	1	0	0	0	0	3	3	26	3	20	1	1	0
t	2	32	1	3	18	1	1	19	4	16	3	4	54	5	5	137	17	3	0	2
T	1	2	7	3	18	0	0	4	0	0	1	1	7	2	28	5	89	5	0	3
V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
v	74	0	45	30	29	7	22	1	10	0	27	16	8	5	20	1	29	216	8	70
Z	7	3	20	8	4	0	3	0	31	0	2	2	0	7	4	1	2	8	54	21
z	4	2	15	6	5	0	0	0	11	0	0	1	1	2	4	0	2	11	6	32
X	15	8	25	22	26	7	13	11	17	6	16	14	20	7	25	13	20	26	1	27
%	0.41	0.60	0.26	0.40	0.49	0.54	0.76	0.17	0.57	0.71	0.50	0.54	0.47	0.68	0.10	0.35	0.27	0.60	0.63	0.15

LP3

	b	C	D	d	f	G	g	h	J	k	m	n	p	S	s	t	T	v	Z	z
b	103	19	26	62	53	1	32	13	34	3	8	9	3	31	22	14	24	29	2	10
C	2	22	0	2	4	0	1	1	2	6	0	0	5	1	2	9	2	1	0	0
D	6	3	33	19	4	1	5	2	10	0	4	3	0	5	3	2	5	12	0	7
d	29	6	21	51	6	2	28	2	36	2	5	5	9	21	13	5	11	10	3	18
f	11	55	9	18	151	0	10	13	15	32	2	3	41	98	71	39	68	14	2	2
G	1	0	1	2	0	10	0	0	1	0	5	5	0	1	0	0	0	1	1	3
g	32	9	16	62	9	4	103	5	62	1	4	4	7	21	13	8	6	30	5	17
h	4	18	2	2	7	0	2	32	2	10	4	2	23	8	8	42	8	2	0	0
J	2	5	6	7	0	0	6	2	15	2	3	1	0	3	2	2	1	3	0	2
k	2	36	0	5	23	0	3	9	5	43	4	0	37	11	7	36	18	1	0	0
m	10	5	9	6	6	7	9	4	7	1	144	96	6	1	7	1	2	14	4	5
n	12	2	8	4	4	20	8	0	7	1	53	85	1	2	4	5	1	8	7	10
p	14	63	2	3	29	0	4	36	1	34	2	3	112	22	24	91	24	2	2	2
S	1	1	0	0	5	1	0	0	1	0	2	0	2	12	2	2	3	0	0	0
s	1	4	2	0	6	1	1	2	2	1	0	3	4	15	8	2	6	1	1	1
t	11	73	4	4	26	0	3	11	9	24	2	1	62	22	21	70	28	8	1	6
T	1	11	0	4	9	0	0	3	6	4	0	0	4	19	13	8	34	1	0	0
V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
v	66	11	68	40	33	8	47	1	53	4	26	7	16	27	31	6	33	131	24	52
Z	0	1	8	3	2	0	1	0	5	0	0	0	2	7	3	0	2	11	1	4
z	5	4	12	10	5	2	7	0	13	0	2	0	1	5	3	3	4	15	4	12
X	28	63	47	32	59	10	51	18	95	25	37	40	46	40	45	46	50	70	12	47
%	0.30	0.05	0.12	0.15	0.34	0.15	0.32	0.21	0.04	0.22	0.47	0.32	0.29	0.03	0.03	0.18	0.10	0.36	0.01	0.06

HP1

	b	C	D	d	f	G	g	h	J	k	m	n	p	S	s	t	T	v	Z	z
b	165	0	15	2	35	0	8	3	0	0	25	6	10	0	1	2	11	21	0	0
C	0	350	0	0	4	0	0	0	10	0	0	0	0	27	0	0	2	0	0	2
D	2	0	104	1	2	2	0	0	0	0	6	10	0	0	0	0	16	16	1	1
d	6	0	13	307	2	2	13	0	4	0	3	16	1	0	1	2	5	6	0	1
f	9	2	6	0	295	2	1	6	0	0	1	4	35	0	0	0	52	15	0	0
G	0	0	1	0	0	34	0	0	0	0	1	0	0	0	0	0	0	1	0	0
g	12	0	6	7	6	8	285	6	1	1	1	0	2	0	1	0	3	12	0	0
h	0	0	2	0	2	0	0	49	0	0	0	2	13	1	0	0	1	0	0	0
J	0	16	3	0	3	0	2	0	334	1	0	1	1	7	0	0	1	1	4	1
k	1	0	1	0	6	0	3	17	0	180	1	1	31	0	1	2	7	0	0	0
m	1	0	2	1	4	3	0	0	0	0	157	18	0	0	0	0	2	3	0	0
n	2	0	4	0	0	3	0	0	0	0	22	154	0	0	0	0	0	0	0	1
p	9	0	0	2	7	0	0	46	2	3	1	2	215	0	0	1	6	1	0	0
S	0	6	0	0	0	0	0	0	2	0	0	0	0	330	3	1	1	0	0	0
s	0	0	0	0	11	0	1	0	0	0	2	0	0	3	271	0	15	0	0	5
t	1	9	0	3	7	1	2	7	2	4	1	6	26	0	1	366	14	4	0	0
T	2	1	10	0	15	1	0	0	1	2	3	9	4	0	1	2	151	2	0	1
V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0
v	113	1	57	10	35	12	10	1	3	0	55	16	12	0	1	1	18	254	3	1
Z	3	2	6	0	0	0	1	0	15	0	1	0	0	10	0	0	1	2	56	1
z	4	0	18	5	4	0	1	0	0	0	1	0	1	1	9	0	8	9	2	206
X	14	1	18	4	14	14	6	4	5	1	17	29	16	2	0	3	20	23	0	1
%	0.48	0.90	0.39	0.90	0.65	0.41	0.86	0.35	0.88	0.94	0.53	0.56	0.59	0.87	0.93	0.96	0.45	0.68	0.85	0.93

HP2

	b	C	D	d	f	G	g	h	J	k	m	n	p	S	s	t	T	v	Z	z
b	188	1	17	0	28	3	0	1	0	0	37	4	13	1	3	0	9	17	1	0
C	0	343	0	0	5	0	0	0	35	0	0	0	1	18	2	2	0	0	0	0
D	6	1	90	6	7	0	1	0	0	0	1	6	0	0	2	0	13	16	0	3
d	3	1	15	299	5	0	7	0	5	1	4	7	2	2	4	5	2	0	0	1
f	6	2	7	0	276	1	4	2	0	0	5	1	23	1	0	0	68	26	0	0
G	0	0	3	2	0	34	1	0	0	0	0	1	1	0	0	0	0	0	0	0
g	9	0	7	4	0	13	291	2	3	4	2	1	1	0	0	0	6	6	0	0
h	0	0	1	0	2	0	0	73	0	0	1	2	8	0	0	0	2	0	0	0
J	0	28	0	0	3	0	0	0	316	1	2	0	0	6	0	1	1	1	0	0
k	3	0	0	0	8	2	17	13	3	180	4	0	26	0	0	1	4	0	0	0
m	13	0	8	2	7	3	0	0	0	0	167	18	3	0	0	0	1	3	0	0
n	2	0	15	2	3	6	2	0	0	0	17	206	3	1	0	0	1	2	0	0
p	12	1	2	0	9	0	0	46	3	1	3	0	271	1	0	7	5	3	0	0
S	0	7	0	0	2	0	0	0	2	0	5	0	0	336	7	0	0	0	0	0
s	0	2	0	0	11	0	0	0	0	0	0	0	1	6	247	2	44	0	1	8
t	1	5	0	4	6	0	1	3	4	12	0	1	11	0	0	343	12	3	0	1
T	0	0	14	1	11	0	0	0	1	0	0	1	1	0	1	0	96	0	0	0
V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
v	74	1	70	1	32	7	2	0	0	0	34	6	7	0	2	0	28	271	8	0
Z	0	1	1	1	1	0	0	0	11	0	0	0	0	15	0	0	0	1	60	5
z	0	0	11	4	3	0	0	0	0	0	0	0	0	0	10	1	10	5	2	207
X	14	2	20	5	16	9	1	3	2	4	13	12	12	3	3	3	33	18	0	4
%	0.57	0.87	0.32	0.90	0.63	0.44	0.89	0.51	0.82	0.89	0.57	0.77	0.71	0.86	0.88	0.94	0.29	0.72	0.83	0.90

HP3

	b	C	D	d	f	G	g	h	J	k	m	n	p	S	s	t	T	v	Z	z
b	192	0	7	5	8	1	36	15	0	0	37	10	49	0	0	2	7	5	0	1
C	0	317	1	1	1	0	0	0	32	0	0	0	2	18	1	5	1	0	0	0
D	4	0	103	4	5	0	0	0	0	0	3	5	0	0	3	0	18	19	0	1
d	2	1	8	303	3	0	3	1	3	1	5	12	1	1	0	20	2	2	0	0
f	8	1	5	1	345	0	4	6	1	0	4	0	21	0	1	1	71	23	0	0
G	0	0	0	0	0	27	2	0	0	0	3	1	0	0	0	0	0	0	0	0
g	5	1	2	3	0	19	254	2	2	17	3	2	4	1	0	0	0	3	0	0
h	0	0	0	0	0	0	0	54	1	0	0	0	2	0	0	0	0	2	0	0
J	0	53	2	2	0	1	1	0	321	4	0	1	1	5	0	1	0	1	1	0
k	0	0	2	0	0	0	15	11	1	162	1	0	8	1	0	1	2	1	0	0
m	8	1	1	4	2	1	1	2	1	0	162	12	4	0	0	1	1	1	0	0
n	3	0	11	3	1	7	0	1	0	2	20	209	3	0	0	0	3	2	0	1
p	16	0	0	0	2	0	1	41	3	2	8	1	247	2	0	1	5	1	0	0
S	0	10	0	0	1	0	0	0	2	0	2	0	0	329	5	0	3	0	1	0
s	0	0	0	0	5	0	0	0	0	0	0	0	0	7	245	1	42	0	0	9
t	0	5	0	6	2	0	0	1	3	1	2	0	3	0	1	335	8	3	0	0
T	0	1	5	1	17	0	0	1	0	0	0	2	1	0	1	1	106	6	0	0
V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
v	72	2	82	6	35	15	4	6	0	2	49	7	12	1	1	1	32	293	1	4
Z	0	3	1	0	0	1	0	0	2	0	1	1	1	24	1	0	0	1	63	1
z	1	0	14	4	2	0	0	1	0	0	0	3	0	0	19	0	15	10	5	211
X	10	9	10	2	10	7	6	6	3	5	10	9	7	4	2	4	12	10	0	4
%	0.60	0.78	0.41	0.88	0.79	0.34	0.78	0.36	0.86	0.83	0.52	0.76	0.67	0.84	0.88	0.90	0.32	0.77	0.89	0.91

APPENDIX F - Confusion matrices for phoneme scoring – Younger Children

FB

	b	C	D	d	f	G	g	h	J	k	m	n	p	S	s	t	T	v	Z	z
b	110	0	13	1	23	0	3	3	0	0	4	4	3	0	1	0	4	17	1	0
C	0	309	0	0	5	0	0	1	4	0	0	1	0	25	2	4	6	0	1	0
D	13	0	112	2	6	0	4	0	0	0	7	5	4	0	0	0	13	22	0	5
d	27	0	16	237	6	0	27	0	6	1	2	7	2	0	2	2	3	11	0	3
f	8	1	1	2	234	2	4	7	0	1	5	2	19	0	2	1	25	8	0	0
G	2	0	1	0	0	36	3	0	0	0	8	0	0	0	1	0	0	1	0	0
g	14	0	6	6	2	5	216	2	2	2	1	2	0	0	0	1	4	6	0	0
h	3	0	2	0	2	0	2	42	1	2	3	3	14	0	0	1	4	1	0	0
J	5	18	3	2	1	1	3	0	300	3	2	3	1	11	1	2	1	8	11	3
k	3	1	0	0	9	1	0	24	0	128	6	4	33	0	1	2	10	2	0	0
m	5	1	5	0	2	1	1	0	0	0	147	23	1	0	1	2	2	5	2	1
n	4	1	6	10	3	7	2	1	0	0	34	150	4	0	1	0	4	12	2	0
p	4	1	1	0	17	1	0	33	2	5	3	3	163	2	0	2	6	5	0	2
S	0	6	0	0	5	0	0	0	1	0	2	0	4	265	10	2	3	2	1	0
s	2	0	0	2	11	0	0	0	0	1	0	0	1	11	198	2	22	0	0	2
t	0	10	2	2	9	0	0	5	1	8	3	1	37	2	2	330	16	0	1	1
T	2	1	4	0	16	0	0	0	0	3	1	1	7	2	3	0	147	2	0	0
V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
v	87	1	38	11	16	5	12	1	0	3	23	10	7	1	1	1	15	176	3	1
Z	2	0	5	1	3	0	0	0	6	0	2	0	0	5	0	0	0	4	38	2
z	3	0	20	2	3	2	1	0	2	0	5	2	3	2	9	0	8	17	2	169
X	18	2	13	6	19	7	13	10	1	2	19	14	11	0	3	2	18	20	1	4
%	0.35	0.88	0.45	0.83	0.60	0.53	0.74	0.33	0.92	0.81	0.53	0.64	0.52	0.81	0.83	0.93	0.47	0.55	0.60	0.88

LP1

	b	C	D	d	f	G	g	h	J	k	m	n	p	S	s	t	T	v	Z	z
b	91	0	11	3	25	0	6	3	1	0	5	3	8	0	0	0	21	17	0	1
C	1	297	0	1	4	0	1	1	8	1	1	1	8	43	4	6	3	0	1	0
D	15	0	78	4	9	0	2	0	1	0	3	4	1	0	3	0	12	11	1	5
d	16	2	21	234	5	2	20	1	10	0	7	5	3	0	1	5	14	12	0	4
f	15	2	6	5	199	0	0	9	1	4	6	1	35	1	1	0	49	18	0	1
G	1	0	0	1	0	26	2	0	0	0	4	1	0	0	0	0	0	2	0	0
g	12	0	6	9	1	8	207	4	1	5	4	0	3	1	0	1	1	12	0	2
h	0	1	1	1	2	0	1	30	0	3	3	1	9	1	0	0	0	0	0	0
J	5	14	3	4	1	0	7	0	276	2	2	0	1	15	1	1	4	5	9	5
k	1	1	3	3	6	0	5	19	0	153	4	1	37	1	1	6	10	2	0	0
m	4	0	4	0	5	4	1	1	2	0	144	31	3	0	0	0	0	3	0	0
n	7	0	3	2	1	11	2	0	0	1	44	142	4	0	0	2	2	14	0	2
p	10	1	0	0	11	0	0	43	1	4	3	2	145	1	1	2	14	4	0	0
S	0	7	0	0	10	0	1	0	2	0	1	0	2	241	24	0	2	0	0	1
s	2	1	3	1	15	0	2	0	0	2	1	0	4	13	186	1	18	0	0	10
t	4	16	1	4	13	0	2	9	2	8	2	0	38	0	7	316	16	3	0	1
T	3	2	6	0	20	0	0	0	0	0	0	3	8	0	6	2	97	6	0	0
V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
v	87	2	50	12	31	2	16	3	2	2	14	14	8	1	2	1	20	174	3	8
Z	2	0	7	1	2	1	1	0	10	0	1	0	1	13	0	0	0	3	46	8
z	4	0	18	4	3	0	2	0	2	0	0	2	0	1	7	0	6	13	6	137
X	21	6	12	10	22	7	12	6	0	2	10	17	19	5	4	3	20	22	1	7
	0.30	0.84	0.33	0.78	0.52	0.43	0.71	0.23	0.87	0.82	0.56	0.62	0.43	0.72	0.75	0.91	0.31	0.54	0.69	0.71

LP2

	b	C	D	d	f	G	g	h	J	k	m	n	p	S	s	t	T	v	Z	z
b	78	2	18	16	26	2	9	3	5	0	10	4	4	1	11	2	11	13	1	7
C	0	208	2	3	7	1	0	3	6	0	0	0	5	36	4	38	1	3	1	2
D	19	3	96	11	6	1	7	2	4	0	7	6	4	1	12	1	15	25	2	20
d	15	1	14	114	5	1	19	0	24	2	5	1	3	4	11	6	6	18	2	14
f	16	8	7	7	175	2	5	7	6	2	7	5	32	7	46	10	57	10	1	5
G	0	0	0	1	1	23	1	0	0	0	6	1	0	1	1	0	0	2	0	0
g	18	2	6	37	5	2	195	2	19	5	2	3	8	3	5	6	2	10	1	9
h	4	3	0	3	3	0	2	26	2	3	2	0	13	4	6	22	4	0	0	2
J	3	7	8	16	3	1	5	0	180	1	2	0	5	21	3	5	7	8	7	5
k	4	30	1	1	5	1	14	28	6	107	4	0	23	3	11	46	7	3	0	2
m	7	1	4	4	5	7	2	0	0	1	125	33	3	0	2	1	3	5	0	2
n	4	0	7	8	5	17	7	1	3	1	52	137	4	0	2	2	0	8	3	9
p	4	11	4	3	22	0	0	34	9	8	1	5	130	4	13	64	13	0	0	0
S	0	14	0	1	2	0	0	0	3	2	3	0	4	203	7	5	9	1	2	1
s	1	0	1	1	13	0	1	0	4	0	3	0	5	10	34	4	24	2	0	0
t	3	40	0	3	12	1	1	14	9	13	4	2	55	3	12	115	18	6	0	2
T	0	3	1	5	20	1	1	0	2	3	3	1	11	1	33	8	71	6	1	1
V	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
v	70	3	31	30	31	2	10	4	13	3	27	16	8	5	13	4	19	147	6	48
Z	6	3	5	2	2	0	3	0	20	0	0	0	2	10	4	0	4	6	30	6
z	8	3	27	4	0	1	3	0	3	0	2	1	1	0	3	0	10	21	5	32
X	29	11	16	17	37	3	13	5	12	5	25	19	17	9	13	14	17	31	3	17
%	0.27	0.59	0.39	0.40	0.45	0.35	0.65	0.20	0.55	0.69	0.43	0.58	0.39	0.62	0.14	0.33	0.24	0.45	0.46	0.17

LP3

	b	C	D	d	f	G	g	h	J	k	m	n	p	S	s	t	T	v	Z	z
b	50	14	8	30	42	1	18	9	18	5	5	6	6	12	17	7	14	19	4	5
C	1	21	0	0	4	0	0	0	3	4	1	0	5	8	5	5	0	0	0	2
D	11	5	24	15	4	3	14	1	11	2	2	6	2	6	7	3	11	17	5	7
d	29	10	27	54	15	0	30	4	34	3	5	7	8	25	20	8	7	16	2	15
f	19	54	11	14	122	2	14	12	17	20	1	6	36	69	41	41	45	13	0	3
G	1	0	1	0	0	9	0	0	2	1	13	1	0	0	1	0	0	2	0	2
g	32	12	16	51	10	7	84	6	41	5	7	3	2	19	9	5	8	22	6	14
h	3	10	3	4	8	0	3	23	10	15	4	9	19	7	5	36	7	3	0	0
J	7	2	7	2	2	0	6	0	15	1	1	5	3	1	7	1	3	9	0	3
k	3	26	1	6	12	3	2	8	4	25	3	3	33	8	7	28	11	0	0	2
m	7	2	10	7	10	6	5	2	13	1	93	68	9	3	4	5	5	13	4	5
n	9	5	7	12	7	12	11	1	9	2	57	66	3	6	4	2	8	22	3	12
p	9	37	5	6	24	0	8	30	2	27	5	0	70	17	18	58	20	4	1	3
S	0	4	0	1	4	0	1	0	0	2	1	0	6	9	4	2	5	0	0	2
s	1	3	4	2	10	0	0	0	2	2	0	1	4	17	10	7	7	3	1	1
t	12	67	3	4	29	0	2	13	2	27	12	1	56	11	18	63	18	3	1	0
T	6	17	3	5	21	0	3	1	6	7	6	2	20	18	23	9	41	6	0	3
V	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
v	59	10	39	25	23	14	34	1	40	6	25	15	12	31	18	12	20	93	17	33
Z	7	1	2	3	1	2	7	0	4	1	0	0	2	2	3	0	1	4	2	3
z	4	3	6	5	4	1	3	0	7	2	1	3	1	8	5	2	7	12	2	14
X	34	52	50	52	46	11	39	16	94	19	32	36	29	56	31	28	57	72	9	60
%	0.16	0.06	0.11	0.18	0.31	0.13	0.30	0.18	0.04	0.14	0.34	0.28	0.21	0.03	0.04	0.20	0.14	0.28	0.04	0.07

HP1

	b	C	D	d	f	G	g	h	J	k	m	n	p	S	s	t	T	v	Z	z
b	120	0	9	5	24	0	6	2	1	2	10	11	7	0	1	1	6	8	0	0
C	1	302	0	0	11	0	0	0	8	1	0	1	0	32	5	6	5	0	3	3
D	16	0	108	7	10	2	2	1	0	0	10	6	6	0	0	2	18	21	3	3
d	16	0	14	253	3	1	15	0	1	2	5	13	7	0	0	2	5	17	0	2
f	11	6	3	1	223	1	3	8	5	6	12	8	32	1	3	0	33	13	0	0
G	0	0	0	1	0	28	2	0	0	0	2	0	0	0	0	0	0	0	0	0
g	9	0	6	6	1	7	236	2	5	3	4	4	5	0	0	0	4	13	1	1
h	4	0	1	2	1	0	3	40	2	2	1	1	13	0	0	0	4	0	0	0
J	1	26	5	5	0	0	0	0	287	0	2	3	1	12	0	1	1	5	5	3
k	2	6	0	0	4	2	2	24	1	129	3	1	44	0	1	1	2	1	0	0
m	6	0	3	2	5	4	1	0	0	0	138	8	3	0	0	0	2	2	0	1
n	2	0	2	6	1	5	0	0	0	0	23	117	7	0	0	0	2	2	2	0
p	4	1	2	0	11	0	1	36	4	1	2	2	153	0	0	1	6	2	0	0
S	0	3	0	0	1	0	1	0	0	0	0	1	1	251	6	0	4	0	0	0
s	0	0	1	0	15	1	0	0	0	0	1	2	3	7	205	2	15	2	0	2
t	2	7	0	5	12	0	3	11	0	11	0	4	23	1	1	321	19	2	0	0
T	0	1	5	2	13	1	0	0	0	1	3	2	8	0	6	0	129	4	0	1
V	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
v	85	5	44	7	31	7	12	1	2	3	46	21	10	0	5	0	19	181	6	2
Z	3	0	8	2	2	0	2	0	4	0	1	0	1	10	0	0	1	7	45	2
z	3	0	15	5	8	1	0	0	0	0	0	0	0	4	10	1	7	20	2	151
X	19	0	19	7	17	10	9	2	2	2	13	23	15	1	4	2	15	16	0	2
%	0.39	0.85	0.44	0.80	0.57	0.40	0.79	0.31	0.89	0.79	0.50	0.51	0.45	0.79	0.83	0.94	0.43	0.57	0.67	0.87

HP2

	b	C	D	d	f	G	g	h	J	k	m	n	p	S	s	t	T	v	Z	z
b	133	0	9	1	11	5	2	1	1	0	34	7	11	0	1	0	8	6	0	1
C	1	302	0	0	8	0	1	1	28	1	0	0	1	35	4	5	4	0	0	0
D	9	0	89	1	7	1	0	0	1	0	8	6	0	0	0	0	17	20	1	3
d	7	2	12	253	3	1	15	0	6	2	4	7	4	0	0	3	5	5	0	4
f	0	2	5	1	216	0	3	5	0	2	5	1	23	1	2	0	44	13	0	1
G	0	0	1	1	0	20	6	0	0	0	2	0	0	0	0	0	0	1	0	0
g	6	0	3	5	4	13	248	8	2	10	3	1	2	0	0	0	1	5	0	0
h	1	0	2	0	2	0	0	40	0	0	1	1	12	1	0	0	2	1	0	0
J	0	38	2	1	1	1	0	0	277	1	1	2	0	12	1	3	1	1	6	1
k	2	2	1	0	6	2	18	20	2	148	2	0	27	0	0	2	0	1	0	0
m	22	0	7	3	7	1	1	1	1	0	139	12	4	0	0	0	4	2	0	0
n	3	0	6	3	1	4	1	1	0	0	17	163	2	0	0	0	3	5	0	0
p	8	0	3	1	7	0	0	42	3	1	2	2	221	1	0	2	4	1	0	0
S	0	5	0	0	2	0	0	0	2	0	4	0	0	250	16	1	4	0	3	1
s	0	0	0	0	26	0	0	0	0	0	0	0	0	7	205	1	56	1	0	9
t	2	9	0	8	5	0	0	3	6	7	0	2	17	1	2	301	11	1	0	0
T	3	1	9	0	19	0	0	0	0	0	0	1	3	2	2	0	90	4	0	1
V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
v	79	1	52	3	31	9	4	1	2	0	28	5	7	0	1	0	17	201	5	2
Z	0	1	1	1	1	0	0	0	7	0	0	0	0	12	0	0	2	5	45	0
z	0	1	13	4	9	0	0	0	0	0	0	0	0	1	15	0	12	12	1	155
X	24	4	22	6	30	12	4	3	2	2	19	21	11	3	5	4	14	21	1	2
%	0.44	0.82	0.38	0.87	0.55	0.29	0.82	0.32	0.81	0.85	0.52	0.71	0.64	0.77	0.81	0.93	0.30	0.65	0.73	0.86

HP3

	b	C	D	d	f	G	g	h	J	k	m	n	p	S	s	t	T	v	Z	z
b	150	0	4	3	4	0	20	11	0	0	40	13	25	2	1	0	4	5	0	0
C	0	239	1	0	4	0	1	1	35	1	0	0	5	24	5	8	4	1	2	0
D	2	2	103	5	4	0	1	3	0	0	11	9	2	0	0	0	20	19	0	2
d	7	0	15	263	3	2	9	1	15	1	6	15	5	1	0	24	12	3	0	1
f	9	3	8	3	276	2	5	8	2	0	5	1	15	1	0	4	40	26	0	2
G	0	0	0	0	0	19	2	0	0	0	0	1	0	0	0	0	0	0	0	0
g	6	1	6	6	0	13	207	11	1	10	4	3	5	1	2	1	4	7	1	2
h	0	0	0	0	2	0	1	42	1	0	0	1	4	0	0	0	0	2	0	0
J	0	60	5	2	0	0	1	0	250	2	1	1	2	7	1	1	0	1	4	2
k	3	3	0	0	4	2	23	7	2	137	1	0	8	1	2	0	2	2	0	0
m	6	0	2	4	2	6	1	3	1	2	133	4	2	0	2	0	0	0	0	0
n	1	0	9	2	1	11	0	3	1	0	12	158	3	0	1	0	5	0	0	0
p	14	2	3	1	4	0	4	29	4	7	10	2	200	0	0	2	1	1	1	0
S	2	8	0	1	5	0	1	0	0	0	0	0	0	277	15	1	3	0	1	0
s	1	1	1	0	13	2	1	0	0	0	5	1	1	16	175	2	44	2	0	12
t	2	5	2	2	4	0	1	0	7	2	1	1	10	2	4	278	8	1	0	0
T	2	1	5	2	20	0	1	1	2	0	1	5	4	1	7	6	85	12	0	0
V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
v	69	2	60	5	29	8	5	3	0	1	33	13	16	2	2	5	27	207	4	0
Z	0	0	1	0	1	0	0	0	2	0	1	0	1	8	0	0	2	3	46	8
z	5	1	12	1	8	1	0	1	0	2	1	4	0	1	12	1	23	19	6	168
X	9	6	12	2	11	5	10	11	8	3	13	13	6	4	5	1	8	10	1	4
%	0.52	0.72	0.41	0.87	0.70	0.27	0.70	0.31	0.76	0.82	0.48	0.64	0.64	0.80	0.75	0.83	0.29	0.64	0.70	0.84