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Components of Auditory Closure

Steven Glen Madix
University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a dissertation written by Steven Glen Madix entitled "Components of Auditory Closure." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Speech and Hearing Science.

James W. Thelin, Major Professor

We have read this dissertation and recommend its acceptance:

Patrick N. Plyler, Mark S. Hedrick, John C. Malone

Accepted for the Council:
Dixie L. Thompson

Vice Provost and Dean of the Graduate School

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Anne Mayhew
Vice Chancellor and Dean of
Graduate Studies

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COMPONENTS OF AUDITORY CLOSURE

A DISSERTATION
PRESENTED FOR THE
DOCTOR OF PHILOSOPHY
DEGREE
THE UNIVERSITY OF TENNESSEE, KNOXVILLE

STEVEN GLEN MADIX
AUGUST, 2005

DEDICATION

This dissertation is dedicated to my ultimate supporter, my best friend, my wife, Christy, and to my sons, David Keith and John Louis. This work is also dedicated to my mother and father, Marshal Keith and Carleen, who have always encouraged me to do what my heart told me. My second parents, Louis and Cora, have provided so much support and encouragement to me that it is hard to imagine how I would have completed my program without them as well.

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ABSTRACT

Auditory closure (AC) is an aspect of auditory processing that is crucial for understanding speech in background noise. It is a set of abilities that allows listeners to understand speech in the absence of important information, both spectral and temporal. AC is evaluated using monaural low-redundancy speech tasks: low-pass filtered words (LPFW), time-compressed words (TCW), and words-in-noise (WiN). Although not previously used, phonemic restoration with words (PhRW) is also a speech task that has been proposed as a measure of AC. In the present study, four tasks of AC, that are listed above, were used to evaluate AC skills in 50 adult females with normal hearing. Using pair-wise correlations, there were no significant relationships among LPFW, TCW, and WiN. As a result, these three tasks were considered to be independent components of AC that represented the AC abilities of spectral reconstruction, temporal resolution, and auditory induction, respectively. Multiple linear regression analysis with LFPW, TCW, and WiN as variables revealed that PhRW is accomplished using temporal resolution. The findings of this study show that no single task of AC is representative of the entire process and that further research is warranted to more completely define the skills that make AC possible.

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I. INTRODUCTION

Auditory closure (AC) is the perceptual process by which partial auditory information is integrated into a whole (Nicolos, Harryman, & Kresheck, 1989; Stach, 1997; Mendel, Danhaurer, & Singh, 1999; Bellis, 2003). This ability is demonstrated when there is understanding of a degraded speech message. Because of the less than ideal listening situations that usually occur in daily conversation, AC is considered a crucial component for understanding speech (Bellis, 2003.) Investigators of central auditory processing or auditory processing consider it to be one component of a group of auditory processing abilities (ASHA, 1995; Bellis, 2003).

Though some investigators have considered AC as a central auditory processing function, equal discussion has been given to the fact that AC also depends on the acoustical characteristics of the speech signal that are believed to be analyzed lower in the auditory system. Bellis (2003) has stated that AC depends on both the redundant intrinsic and extrinsic properties of the speech message. Intrinsic properties refer to the neurological characteristics of the ascending auditory pathway and the manner in which information in the speech signal is replicated many times through its progression to the auditory cortex. Extrinsic properties refer to the redundant properties inherent to the speech signal itself and the manner in which a listener uses linguistic knowledge to anticipate or expect portions of the speech signal based on linguistic rules. Mendel et al. (1999) have related this process to inductive and deductive reasoning skills of the listener through use of lexical knowledge in combination with the contextual information present in the speech signal. These two views suggest that AC is not entirely a central process, but rather that it is due to an interaction of peripheral and central functions.

When assessing AC, or auditory processing in general, cognitive processes are involved that influence the results. It has been shown that when listening groups are matched for cognitive processing, results that were attributed to diminished auditory processing may disappear in populations that have been diagnosed with auditory processing deficits (Humes & Christopherson, 1991). Based on these data, it is evident that cognitive factors will always play a role in the assessment of auditory processing. Therefore, whenever AC is evaluated, cognitive abilities need to be taken into account. Otherwise, interpreting individual results and diagnosing auditory processing ability based on comparisons may lead to inaccurate conclusions.

Bellis (2003) examined tasks that she felt should be included as tests of AC. The characteristics of these tests were that they contain speech signals of limited redundancy that require only monaural processing. She considered three types of tasks to be included in the AC classification. The tasks each required the understanding of speech under special conditions of degradation: low-pass filtered speech, time-compressed speech, and speech-in-noise. In personal communication, Bellis, (2005), has expressed the opinion that phonemic restoration (PhR) could be included with these three other tasks. PhR is the ability to perceptually restore masked or deleted segments of speech through the use of an extraneous sound (Warren 1970). Successful completion of each of these tasks depends on specific auditory abilities: AC with reduced spectral content, AC with background noise, AC with temporal compression, and AC with deleted phonemes. Literature addressing these abilities of normal processes in young adults with normal hearing is reviewed below.

Auditory Closure with Reduced Spectral Content

AC with reduced spectral information represents the ability of the listener to understand the speech signal in the absence of frequencies important for speech understanding. It is a spectral reconstruction. French and Steinberg (1947) conducted early studies on high-pass and low-pass filtered speech in normal hearing listeners. More recently, investigators have examined these effects in populations with peripheral and central deficits (Vickers, Moore, & Baer, 2001; Farrer, & Keith, 1981; van Bezooijen, & Boves, 1986). The influence of specific frequency bands on speech understanding has also long been investigated and the importance of these frequency bands, along with their contribution to intelligibility, is demonstrated in the Articulation Index (Beranek, 1947; Fletcher & Galt, 1950; Kryter, 1962; Steeneken, & Houtgast, 1980).

For individuals with normal peripheral auditory function, reduced spectral content tasks are used to determine auditory processing ability. Bornstein, Wilson, & Cambron (1994) used high-pass and low-pass filtered word recognition tests to study speech perception in adults with normal auditory function. They found that speech perception depends on both the frequency cut-off and the rejection rate of the filter.

For the purpose of assessing AC, only low-pass filtered speech is used and therefore, only those results will be reported. In Figures 1 and 2, the results are shown for Bornstein et al. (1994) for low-pass filtered speech. The participants were young adults with normal hearing. In Figure 1, the data demonstrate the effect of different cut-off frequencies for low-pass conditions at a presentation level of 70 dB SPL. Optimal performance of 88% correct word recognition was obtained with a low-pass cut-off of 1700 Hz. Performance decreased systematically to 30% correct word recognition as

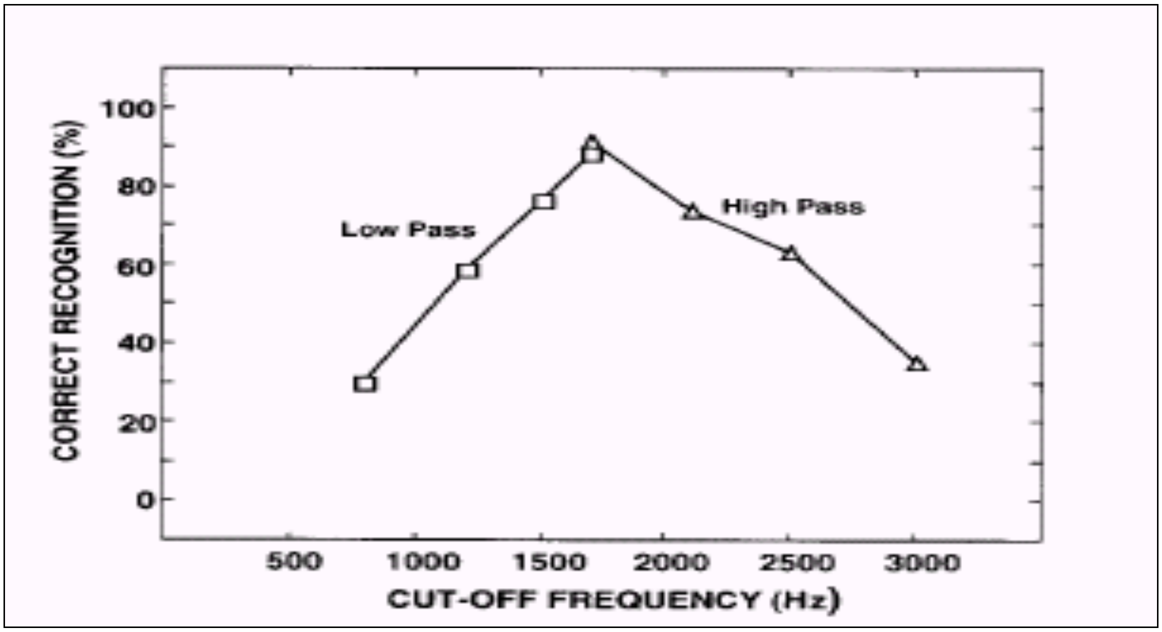

Figure 1: Mean percent correct word recognition for NU No-6 lists presented at 70 dB SPL as a function of cut-off frequency (Bornstein et al., 1994).

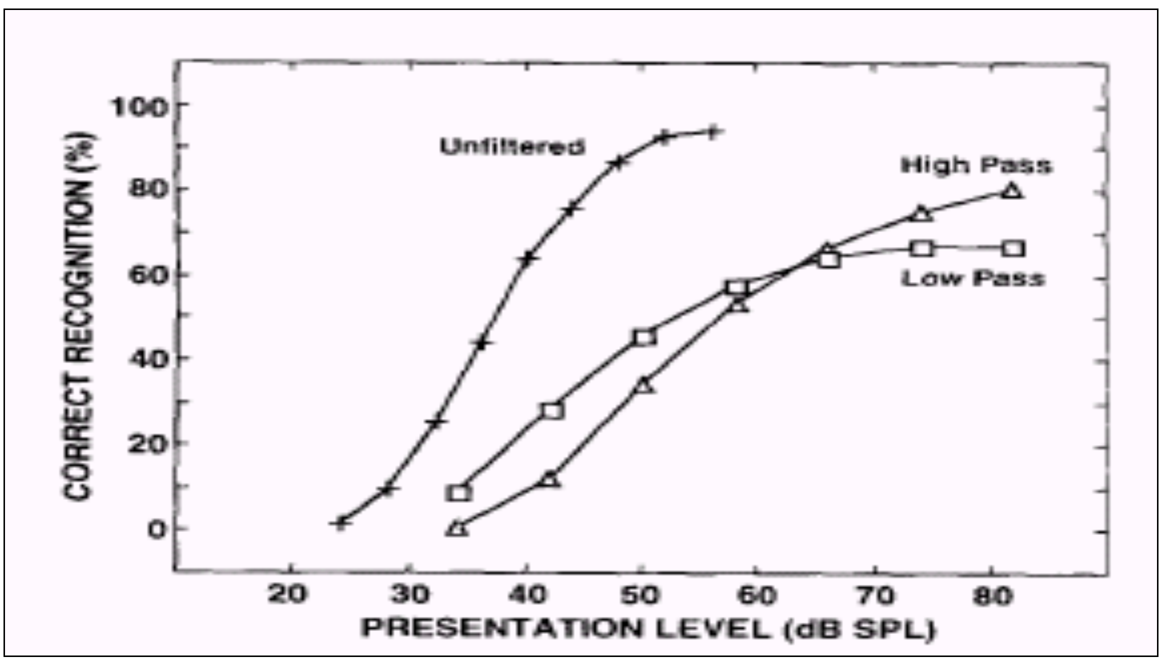

Figure 2: Mean percent correct word recognition for NU-6 lists at low-pass (1500 Hz) and high-pass (2100 Hz) filter conditions as a function of presentation level (Bornstein et al., 1994).

low-pass cut-off was decreased to 800 Hz. With the cut-off frequency at 1500 Hz, performance improves over the range of 35 – 70 dB SPL but remains stable over the range from 70 – 80 dB SPL. These data indicate the effect of high frequency spectral deletion and loudness on word recognition as they relate to young adults with normal hearing.

Auditory Closure with Background Noise

Another form of speech degradation is speech presented with background noise. Speech degraded in this manner represents the listeners' ability to understand speech in the presence of competing background noise. Speech-in-noise tasks can be composed of single words or sentences. In sentence tasks, the correct identification of a key word is used to score the task. Examples of sentence speech-in-noise tasks are the Speech Perception in Noise (SPIN) Test (Kalikow, Stevens, & Elliott, 1977) or SPIN-Revised (SPIN-R) (Bilger, 1984), the Selective Auditory Attention Test developed by Cherry (1983), the Auditory Figure Ground subtest of the SCAN, -A and -C (Keith, 1986; 1994; 2000), the Ipsilateral Competing Message portion of the Synthetic Sentence Identification Test by Jerger and Jerger (1974), and Hirsh's CID Auditory Test W-22 (Hirsh et al., 1952) with ipsilateral competing speech spectrum noise (Katz & Fletcher, 1997).

The CID W-22 word lists, which are found on the Central Test Battery CD (Katz & Fletcher, 1997) are a speech-in-noise test that is conducted monaurally with ipsilateral competing speech spectrum noise. The test has normative data for right and left ears in children and adults with a +5 dB signal to noise ratio (SNR).

Auditory Closure with Temporal Compression

Temporal compression is the reduction in length of a speech signal. Compression of a speech signal taxes the listeners' ability to understand speech by reducing duration and omitting temporal information. One manner in which speech can be time-compressed is by systematically deleting small temporal segments through out the entire message. The segments that remain are fused to reduce the duration of the speech message without altering the frequency spectral characteristics. Listeners are able to understand speech that has been degraded in such a manner through temporal resolution, which has been defined as the ability to "…resolve fast temporal changes over time" (Roberts & Lister, 2004).

Wilson, Preece, Salamon, Sperry, & Bornstein (1994) studied the effects of time compression with single words (NU-6 word lists) for young adult listeners with normal hearing. Compression was varied from 45% (55% of the original signal duration) to 75% (25% of the original signal duration) with a presentation level of 70 dB SPL. In Figure 3, the results indicate that mean word recognition was approximately 90% for the 45%-compression condition and that it decreased systematically to approximately 25% for the 75 % - compression condition. The data indicate that as compression rates exceed 45%, young normal hearing adults begin to decrease in performance with very poor accuracy at the 75% - compression rate.

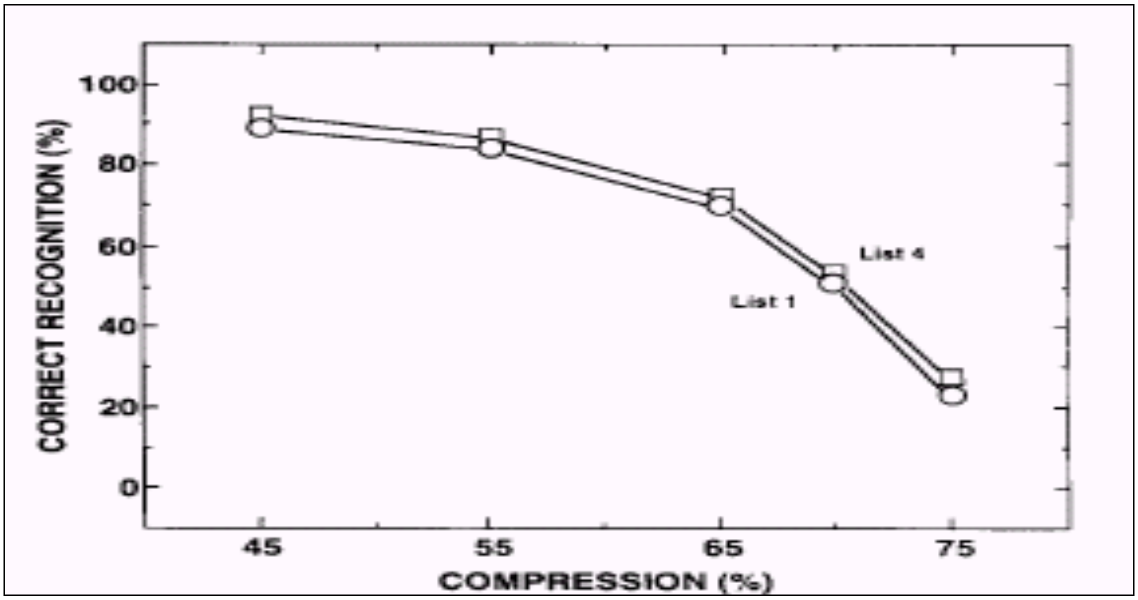

Figure 3: Mean percent correct recognition for the NU-6 lists as a function of compression (Wilson et al., 1994).

Auditory Closure with Deleted Segments of Speech

In PhR tasks, a segment of speech is deleted and replaced with a noise. If the noise has greater amplitude and a broader frequency spectrum than the sound that it replaced, the speech message will be perceived as intact (Warren, 1996; Samuel, 1981a). The restoration is accomplished by a process referred to as auditory induction. A model of auditory induction as it leads to PhR based on the literature can be seen in Figure 4. The model illustrates how auditory induction can occur across "space", which is contralateral induction in a dichotic task, or within "time", which is temporal induction and can be a monaural or binaural task.

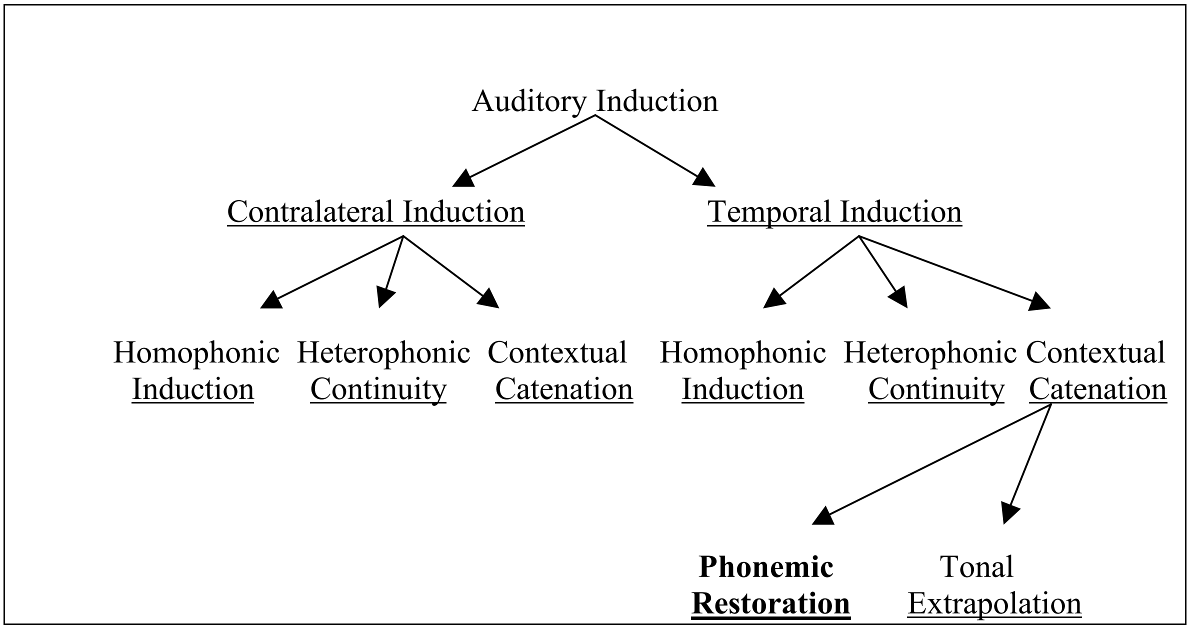

Figure 4: A model of auditory induction as it leads to PhR based on information in the literature (Warren, 1996).

Samuel (1981a) investigated the dependence of PhR on the acoustic and linguistic information present in the speech signal. He concluded that PhR is dependent on both "bottom-up" information, which is the acoustic properties of the speech message, and "top-down" information, which is the listener's lexical knowledge. His conclusions support the idea that PhR, which is very similar to AC, relies on both peripheral and central processes.

Madix, Thelin, Plyler, & Hedrick (2005) studied the dependence of PhR on amount of context in the speech message. There were three speech context conditions: word, phrase, and sentence. In this study, speech signals were presented in the sound-field; however, PhR studies have been conducted using monaural presentations as well. There were two measures of performance: (1) "PhR", which was defined as the perceived intactness of the speech message without regard for accuracy and (2) "accuracy of PhR", which was defined as the accuracy of identification of the replaced phoneme without regard for the perceived intactness. The results showed that accuracy of PhR always exceeded PhR. For the purposes of understanding AC, the most important aspect of performance is that the message was understood correctly (accuracy of PhR) and not whether the illusion of PhR occurred. In Figure 5, accuracy of PhR is shown for the three context conditions in 20 young adult female participants with normal hearing. The results indicated that mean accuracy improved as the amount of context increased – from 74% for the word condition to 97% for the sentence condition.

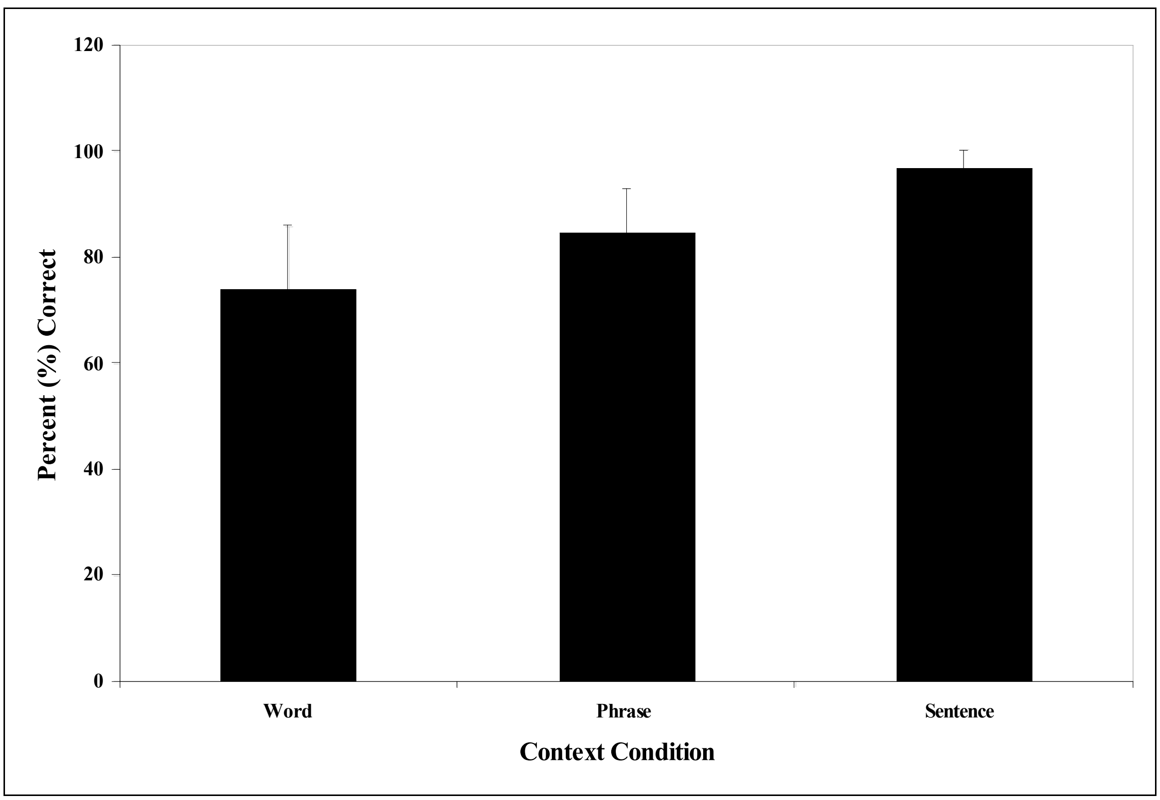

Figure 5: Mean percent correct PhR (and SD) are shown for three context conditions (Madix, Thelin, Plyler, Hedrick, & Malone, 2005).

Rationale

AC is a term used to describe abilities that are believed to be related to each other. AC performance is determined by the use of special skills that allow for the integration of partial auditory information. AC depends on these special skills – and also on general cognitive abilities. AC abilities have been related by the agreement of investigators and not by demonstration of functional similarity or dissimilarity. At present, there is no empirical evidence to indicate that the results of any single test define or completely represent the different abilities included in the concept of AC. As a result, investigators of auditory processes have developed specific tasks to measure the different AC abilities. The purpose of the present study was to determine if there are relationships among these abilities as demonstrated by performance on tests of AC using words.

In the present study, AC abilities in young adults with normal peripheral hearing and no indications of altered auditory or cognitive processing will be tested using linguistic stimuli of minimal length (words with one or two syllables). Since only normal hearing young adults were selected as listeners, only tasks that had normative data for that population were selected. The results of these tests were correlated with each other to determine the strength of relationships among measures of AC ability. Specifically, the following abilities were compared using the following tasks:

1. AC with spectral degradation (low-pass filtering)
2. AC with altered temporal resolution (time-compression),
3. AC with speech in background noise (competing speech spectrum noise), and
4. AC in a PhR paradigm.

II. REVIEW OF LITERATURE

Abilities Related to Central Auditory Processing

Central auditory processing has been defined by the ASHA Task Force on central auditory processing (1995) as "the auditory system mechanisms and processes responsible for behavioral phenomena such as sound localization and lateralization, auditory discrimination, auditory pattern recognition, temporal aspects of audition, and auditory performance decrements with competing and degraded acoustic signals". In recent literature, the term auditory processing has replaced central auditory processing. These process-based functions are divided into major categories that include binaural interaction, temporal patterning, binaural separation, binaural integration, and auditory closure, (Bellis, 2003). Specific auditory behavioral tasks have been developed that test each these functions.

Binaural interaction, also referred to as binaural integration, is the ability of the listener to use both ears in order to fuse auditory information into a meaningful signal. It consists of auditory functions that include localization and lateralization, binaural release of masking, detection of signals in noise, and binaural fusion in time and frequency (Bellis, 2003). The hallmarks of binaural interaction are sound localization and the ability to detect speech in background noise, which is the first step of understanding speech in noise.

Temporal patterning is the ability to recognize acoustic contours of speech (Bellis, 2003) but is accomplished with the help of other auditory processes such as discrimination of differences in auditory stimuli, auditory stimuli sequencing, gestalt pattern perception and trace memory (Musiek & Chermak, 1995; Musiek, Pinheiro, & Wilson, 1980). Temporal patterning enables a listener to detect and use the characteristics of speech that deal with prosody, for instance rhythm, stress, and intonation.

Binaural separation and integration are distinct auditory processes that are related (Bellis, 2003). Separation is the listeners' ability to process auditory stimuli in one ear while simultaneously ignoring a contrasting stimulus in the opposite ear. Integration is the listeners' ability to process different information reaching the ears simultaneously. Binaural separation and integration allow the listener to focus on important speech while ignoring competing speech.

Auditory closure (AC) is the ability to use the redundant intrinsic and extrinsic qualities of speech in order to fill in missing or degraded segments so that the complete message can be understood (Bellis, 2003). Extrinsic information refers to the abundance of information present in the speech signal, whereas intrinsic information refers to the abundance of information and the repetition of that information present in the central auditory system due to the capacity inherent in its richly innervated pathways (Bellis, 2003; Stach, 1997). AC is a crucial component of auditory processing that allows the listener to engage in understandable discourse in the presence of less than ideal listening situations.

The focus of the present study is on the abilities that are believed to be related to and responsible for AC. AC ability is measured behaviorally through the use of monaural low redundancy speech tasks (Bellis, 2003). AC tasks are developed in a manner that reduces the redundancy of the speech (linguistic information) and are administered monaurally in an effort to detect differences between ears that would indicate a breakdown of interhemishpheric sharing of auditory information. The tasks associated with AC ability degrade speech by removing frequencies that are important for speech intelligibility, by introducing background noise that masks portions of the speech signal, and by eliminating the normal temporal characteristics of speech without altering the frequency characteristics. Although it has not been used, deleting segments of speech may be used as a test of AC ability. In personal communication with Bellis (2005), she indicated that PhR could be included with these tasks. Specific tasks that are thought to measure AC ability are low-pass filtered speech, speech in noise, time-compressed speech, and PhR (Bellis, 2003, 2005).

Low-Pass Filtered Speech

Low-pass filtered speech (LPFS) tests are word recognition measures that consist of monosyllabic words that have been band-pass filtered above approximately 800 Hz (Stach 1997). These tests degrade auditory information and test AC by removing spectral content that aids in intelligibility. The amount of degradation is dependant on the cut-off frequency and the rejection rate of the filter (Bornstein et al., 1994). Bornstein and colleagues identify two general rules that apply to LPFS: (1) the lower the cut-off frequency, the poorer the word recognition score and (2) the steeper the rejection rate of the filter, the poorer the word recognition score.

According to Stecker (1992) and Bellis (2003), the first use of LPFS was by Bocca and colleagues (1954) to identify temporal lobe lesions. Since that time, the use of LPFS tasks in the clinical setting has occurred for many different types of patients having neurological deficits (Linden, 1964; Kurdziel, Noffsinger, & Olsen, 1976; Rintelmann, & Lynn, 1983; Mueller, Beck, & Sedge, 1987). Today, LPFS is used more commonly as a test of auditory processing ability. Examples of such measures are the Ivey filtered speech test of the Willeford central test battery (Willeford, 1977), the SCAN, -A and -C (Keith, 1986; 1994; 2000) Filtered Words subtest and the low-pass filtered versions of the Northwestern University No. 6 (NU-6) word lists (female speaker) (Wilson & Mueller, 1984).

Wilson and Mueller (1984) have obtained normative data on young adults for low-pass filtered words (see Figures 1 & 2). There are two, 50 word lists that have a frequency cut-off of 1500 Hz and a rejection rate of 115 dB/octave. The cut-off frequency and rejection rate were selected in order to achieve a 70 to 80 percent correct word recognition performance at a comfortable listening level in young, normal hearing listeners (Bornstein et al., 1994). The compact disk trials (Bornstein et al., 1994) of the low-pass condition indicate that a maximum score of approximately 66% is achieved at presentation levels of 45 dB HL and above (Table 1).

Table 1: Percent correct word recognition (and SD) for low-pass filtered words as a functional of presentation level during compact disc trials for 20 listeners (Bornstein et al., 1994). Results at (65 dB HL) were obtained on 40 listeners.

	Presentation Level (dB HL)						
	15	25	35	45	55	65	(65)
Low-Pass Filtered							
Mean	11.8	32.0	56.4	65.2	67.0	66.6	(66.5)
Standard Deviation	11.1	9.8	10.8	10.5	8.9	11.3	(8.5)

Speech-in-Noise

Speech-in-noise tests have been the most commonly used tasks when evaluating auditory closure ability and have been an interest among cognitive psychologists (Altmann & Shilcock, 1993; Clifton, Frazier, & Rayner, 1994) in examining the effects of noise on speech understanding. The popularity of using speech-in-noise tests comes from the fact that processing speech in background noise is one of the most common complaints of individuals who have problems with auditory processing. The degradation of speech in these tasks is achieved by adding background noise at various levels that mask certain portions of the speech signal. For the purpose of this study, speech will be limited to words in order to limit the redundancy of the speech signal.

Examples of speech-in-noise tests using single words that have normative data are the Auditory Figure Ground subtest of the SCAN,-A and -C (Keith, 1986; 1994; 2000) and the CID W-22 word lists with competing speech spectrum noise (Katz & Fletcher, 1997). The Auditory Figure Ground test is a subtest of the SCAN-A – a test of central auditory function designed for adolescents and adults. The subtest is used to evaluate the listener’s ability to understand words in the presence of multi-talker speech babble noise at a +4 dB SNR. The stimuli consist of a 20 word test list. The Katz Central Test Battery uses CID W-22 word lists presented with a speech spectrum noise at a +5 dB SNR and consists of four lists of 25 words. Results obtained with the CID W-22 word lists, as used in the Katz Central Test Battery, can be seen in Table 2. The results indicate that word recognition in noise gradually improves up to adulthood with a reduction in inter-subject variability.

Table 2: Percent correct word recognition (and SD) for the Central Test Battery-CD Word Recognition Tests in Noise (Katz & Fletecher, 1997)

Age Group	Noise-R % Correct (SD)	Noise-L % Correct (SD)
5	81.0 (8.6)	78.7 (10.1)
6	81.0 (8.6)	78.7 (10.1)
7	81.8 (6.5)	81.4 (8.5)
8	81.8 (6.5)	81.4 (8.5)
9	81.8 (6.5)	81.9 (8.0)
10	84.4 (6.5)	81.9 (8.0)
11	84.4 (6.5)	82.3 (7.5)
Adult	88.7 (6.8)	87.7 (6.7)

Time-Compressed Speech

Time-compressed speech tasks evaluate AC ability by systematically deleting temporal segments without altering the frequency spectrum. They are tasks of temporal processing, but more specifically temporal resolution. Temporal resolution may be defined as the ability to hear sounds when masked by a fluctuating noise signal or resolve fast temporal changes over time (Roberts & Lister, 2004). In time-compressed speech tasks, speech can be accelerated by having the speaker increase their rate of talking or by altering the rate of playback in reference to the original recording (Calearo & Lazzaroni, 1957; Bergman, 1980). Another method used to compress speech, is to electronically eliminate segments of the waveform and move the remaining waveforms together to shorten the sample of speech (Fairbanks & Kodman, 1957). This transformation preserves the power spectrum of the speech while compressing the temporal pattern.

Tasks of temporal processing are distinctly different from tasks of temporal resolution. Temporal processing tasks traditionally use non-speech stimuli, such as noise, and the listener is tasked with identifying gaps or breaks in the noise. These tasks are referred to as gap detection measures. Past experiments have shown associations between temporal processing using gap detection measures and the ability to understand speech that has been acoustically degraded (Gordon-Salant & Fitzgibbons, 1993; Irwin & McAuley, 1987; Snell, Mapes, Hickman, & Frisna, 2002; Tyler, Summerfield, Wood, & Fernandes, 1982).

Tasks of temporal resolution can use speech as stimuli and correct identification of the speech as the measure. Temporal resolution tasks may use sentences and words with varied compression rates. Generally speaking, as compression rates increase, speech intelligibility decreases. In normal hearing adults, difficulty begins to occur when compression rates exceed 45%.

Time-compressed speech tasks can be in the form of sentences (Keith, 2002) or words (Wilson et al. 1994). The present experiment used words as the stimuli. The effects of time compression on the intelligibility of NU-6 (female speaker) have been described in normal hearing adults and the final form of the compressed words are on the *Tonal and Speech Material for Auditory Perceptual Assessment, Disc 2.0* (Wilson & Strouse, 1998). The words are divided into two, fifty word lists, with each compressed at rates of 45% and 65%. Data representing the effects of the different compression rates and presentation levels for normal hearing adults are shown in Table 3. It can be seen that the understanding of time-compressed speech depends on both the amount of compression and presentation level.

Table 3: Percent correct word recognition (and SD) for two compression rates and six presentation levels for 20 listeners (Wilson et al., 1994). Results at (65 dB HL) were obtained on 40 listeners.

	Presentation Level (dB HL)						
	5	15	25	35	45	55	(55)
45% Compression							
Mean	1.1	24.8	63.6	85.4	91.2	93.4	(94.9)
Standard Deviation	2.8	20.4	13.5	9.6	7.8	6.7	(4.2)
65% Compression							
Mean	0.9	14.5	43.0	63.4	75.0	75.0	(75.9
Standard Deviation	2.4	11.1	19.1	19.2	19.3	21.8	(10.2)

Phonemic Restoration

Phonemic restoration (PhR) is the perceptual process by which a listener restores deleted or masked portions of speech through the use of an extraneous sound (Warren, 1970; Warren & Warren, 1970). It is a form of auditory induction, which is a synthesis whereby a sound that has been removed or masked in a signal is perceptually restored (Warren, 1996). It is an illusory perception. A model for the types of auditory induction is shown in Figure 4 based on a compilation of data from the literature on auditory induction. There are two types of auditory induction, contralateral (Warren, 1996, 1984; Eagan, 1948; Thurlow & Elfner, 1959; Butler & Naunton, 1962, 1964) and temporal induction (Warren, 1970, 1984, 1996; Miller & Licklider, 1950; Warren, Obusek, & Ackroff, 1972; Sasaki, 1980; DeWitt & Samuel, 1990). PhR is considered a form of temporal induction, specifically contextual catenation. In PhR, a speech segment is removed and replaced with a broad spectrum noise that serves as a bridge or template to

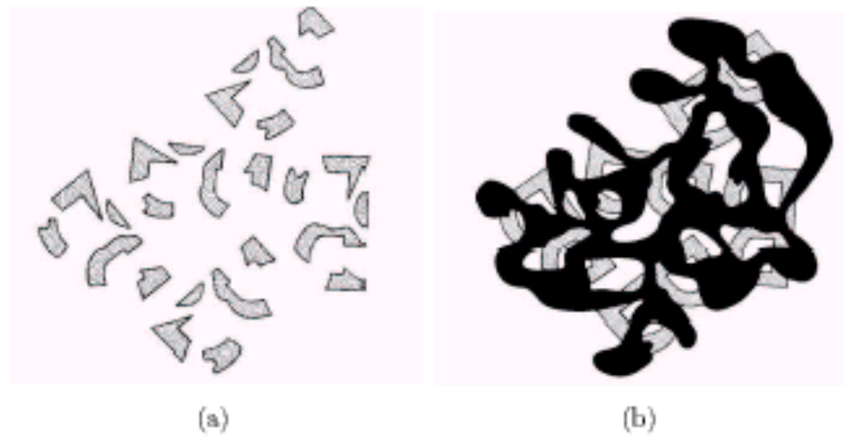

Figure 6: A visual analog of phonemic restoration (Bregman, 1981). (a) Fragments of multiple instances of the letter "B". (b) The same fragments of (a) together with an irregularly shaped occluding pattern.

enable restoration. A visual analog of this process is shown in Figure 6. In this figure, a black matrix serves as the visual equivalent of noise that enables the letters “B” to be recognized.

PhR is the form of contextual catenation that involves speech (Warren, 1970, 1976, 1984; Warren & Obusek, 1971; Warren & Sherman, 1974). Warren (1970) proposed that PhR is a critical process used in everyday communication to restore portions of masked speech. Since Warren’s original study, investigators have examined the circumstances in which PhR optimally occurs (Layton, 1975; Samuel, 1981a; Warren, 1970; Warren & Obusek, 1971). Schematic models of PhR have also been developed which attempt to demonstrate the PhR process (Srinivasan & Wang, 2004; Masuda-Katsuse & Kawahare, 1999; Cooke & Brown, 1993). An example of the model proposed

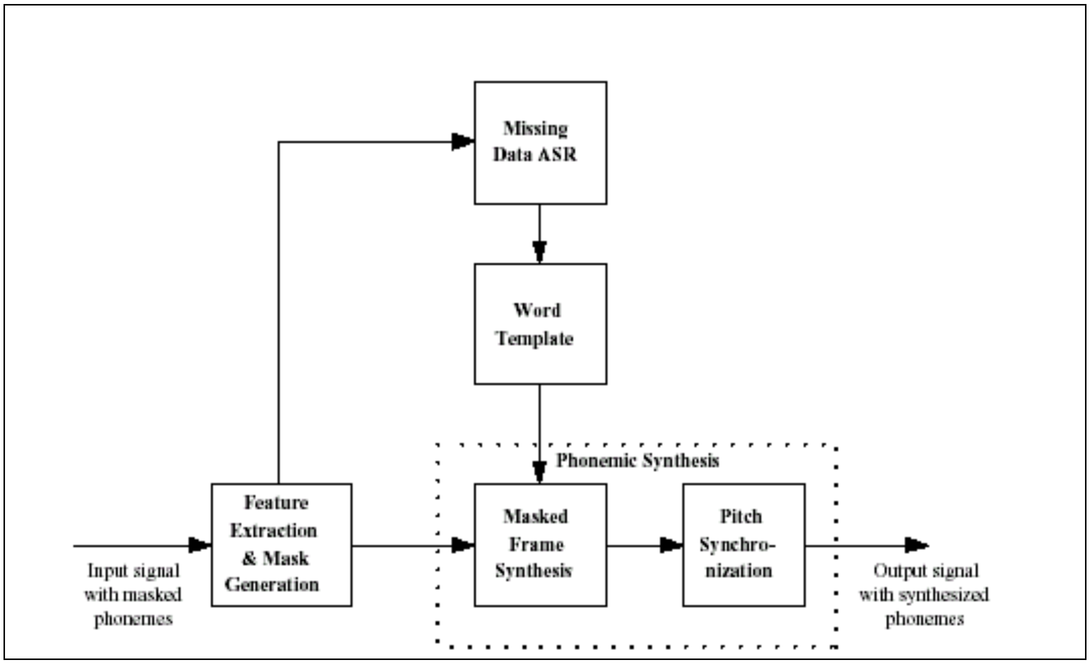

Figure 7: A block diagram of the proposed PhR model by Srinivasan and Wang (2005).

by Srinivasan & Wang (2004) is shown in Figure 7. This model illustrates the perceptual process of replacing the masked phoneme, through feature extraction and use of a word template, in order to synthesize a complete speech signal.

PhR and the accuracy of PhR have been examined as a function of contextual length and age (Madix, Thelin, Plyler, & Hedrick, 2005). Their study used sentences, phrases and words to observe the occurrences of PhR and the accuracy of those restorations in adult listeners. Their results demonstrated that as context decreased, so did accuracy of PhR. Of the contextual conditions examined, single, multi-syllable words were the most difficult achieving accuracy scores that averaged 85% correct for normal hearing young adult females. Although it has not been used specifically as a test of AC, accuracy of PhR appears to be a task of AC ability (Bellis, 2005).

III. METHODS

Participants

Listeners were 50 students in audiology and speech language pathology and in psychology at the University of Tennessee, Knoxville who had standard American English as a native language. Listeners in this group had a mean age of 21.9 years (SD = 2.4 years) and had audiometric thresholds that were ≤15 dB HL in the right ear for the octave frequencies 0.5 through 8 kHz. All listeners were asked a series of four questions that addressed conditions associated with auditory processing disorders. Each of the listeners indicated that she did not have any of the following conditions: (1) auditory processing disorder, (2) attention deficit disorder (ADD), (3) attention deficit hyperactivity disorder (ADHD), (4) dyslexia, or (5) learning disability. Extra-credit for coursework was awarded to the listeners for their participation. Listeners were recruited through advertisements for participating in hearing experiments in the two academic departments.

Experimental Apparatus

Participants were tested individually in a sound treated booth with background noise levels meeting ANSI criteria (ANSI S3.1, 1999). Hearing screenings for each participant were conducted with a two-channel clinical audiometer (Madsen, Orbiter 922) meeting ANSI criteria (ANSI S3.6, 1996) using a supra-aural earphone (Telephonics TDH-39). Experimental tests were recorded on digital compact disks and were delivered from a RCA compact disk player through the clinical audiometer.

Experimental Test Materials

For each of the four experimental tests, the word lists were presented monaurally to the right ear at 65 dB HL. Each test was composed of 50 items and performance was scored in terms of percent correct word recognition. For each test, the signal parameters were selected so that mean performance was less than perfect but greater than 50%.

Words-in-Noise Task. The words-in-noise (WiN) were Lists 4-D (1) & 4-D (2), taken from the Katz Central Test Battery CD (Katz & Fletcher, 1997). The speech spectrum noise was presented at 5 dB below the level of the words. The word lists and test instructions are provided in APPENDIX A.

Time-Compressed Word Task. The time-compressed words (TCW) were List 8-A, taken from the Veterans Administration recording of test materials, *Tonal and Speech Materials for Auditory Perceptual Assessment, Disc 2.0* (Wilson & Strouse, 1998). The word list was a NU-6 list with a time compression rate of 65% with female talker (Wilson et al., 1994). For these conditions, Wilson et al. (1994) found mean word recognition to be approximately 75%. The word lists and test instructions are provided in APPENDIX B.

Low-pass Filtered Word Task. The low-pass filtered words (LPFW) were NU-6, List 3C (female speaker) with a low-pass cutoff frequency of 1500 Hz and 115 dB/octave roll off. The test recording was obtained from the Veterans Administration CD of test materials, *Tonal and Speech Materials for Auditory Perceptual Assessment, Disc 2.0*

(Wilson & Strouse, 1998). For these filtering conditions, young adult listeners with normal hearing were found to have a mean word recognition score of 66.5% (Bornstein, et al. 1994). The word lists and test instructions are provided in APPENDIX C.

PhR Word Task. PhR for words (PhRW) task was created for this study. It was constructed using words that contained enough lexical and morphological information that allowed for deletion of a sound segment. Monosyllable words do not contain enough lexical or morphological information to allow for PhR with the deletion of a sound segment. As a result 50 two-syllable words (spondees) were selected for this task.

The spondees were taken from the Auditec recording of CID W-1 words. Each spondee contained a deleted phoneme that was replaced by a 200 ms cough that filled the void (Figure 8). The location of the deleted phoneme was selected by observing the speech waveform and listening to the word. The location of the deletion was manipulated to minimize coarticulatory effects. The manipulation of words was conducted with Cool Edit-Pro v.2® using the procedure recommended by Samuel (2004) for deleting and replacing phonemes. Selection of test words was based on the results of pilot data obtained before the present study. For speech presented at 65 dB HL, four young adult listeners with normal hearing had a mean score of 62% for the PhRW task. The word lists and test instructions are shown in APPENDIX D.

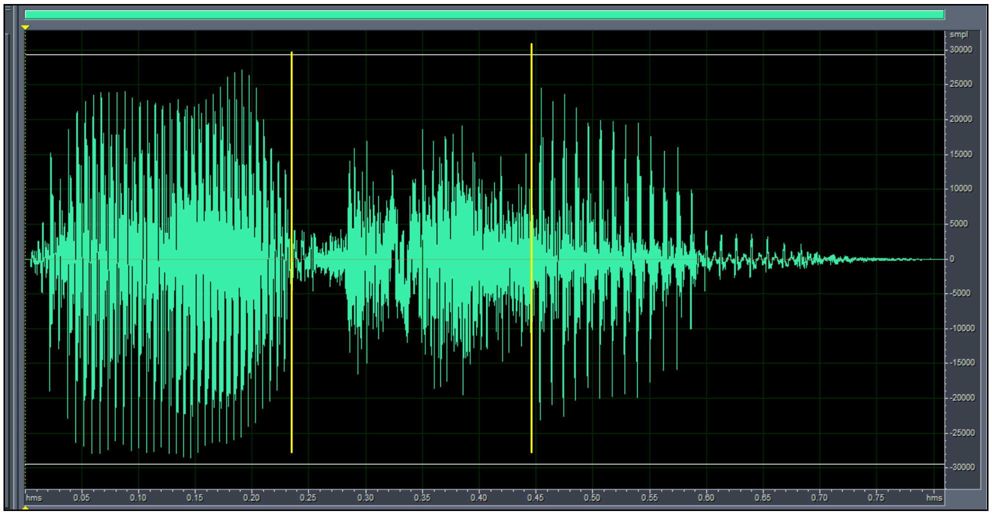

Figure 8: The word "airplane" after phoneme substitution. Between the yellow lines is the position of the 200 ms cough following the deletion of the “pl”.

Experimental Procedure

Each experimental session lasted about 30 minutes. The informed consent (APPENDIX E) was read aloud to each participant and signed. All testing was done in the sound treated audiometric room. Listeners answered the four questions that addressed conditions associated with auditory processing disorders. Of the 60 listeners recruited, 50 met the criteria for inclusion in the study. The order of presentation of the four experimental tests was randomized for each listener. Each experimental test required about 6 minutes to complete with 2 –3 minute breaks given between each test if needed.

IV. RESULTS

The individual results for each listener are shown in APPENDIX F. The mean results for all listeners on the four AC tasks are shown in Table 4. The mean scores ranged from 66.8% to 79.4 % correct indicating that each of the tasks was moderately difficult. The extreme scores for the four tasks were 44% and 94% correct indicating that there were no end effects. The standard deviations (SD) ranged from 7.8% to 10.6% indicating that the variability was substantial among adult listeners with normal hearing and no evidence of auditory processing problems.

The main analyses of the present study were correlations among the four AC tasks. Prior to these analyses, a root arcsine transformation was performed on the percentage correct scores for the four tasks. The results of the correlational analyses are shown in Table 5. The criterion for significance was $p < .05$. There were only two significant correlations: (1) the correlation between PhRW and TCW was highly significant, and (2) the correlation between PhRW and WiN was significant.

Table 4: AC task results for all listeners in percent correct word recognition.

	LPFW	**TCW**	**PhRW**	**WiN**
Mean	66.8%	79.2%	76.2%	74.7%
SD	10.6%	7.8%	8.3%	8.5%

Table 5: Correlations among the transformed results for the four AC tasks. N = 50 for each correlation.

		TCW	WiN	LPFW
PhRW	**Pearson-Correlation**	.500	.351	.208
	Sig (2-tailed)	.000**	.013*	.147
TCW	**Pearson-Correlation**		.226	-.094
	Sig (2-tailed)		.114	.515
WiN	**Pearson-Correlation**			.131
	Sig (2-tailed)			.363

* = Significance at the .05 level of confidence
** = Significance at the .01 level of confidence

The correlation between TCW and WiN was not significant. LPFW was not correlated to any of the other three AC tasks.

The pair-wise correlational analyses indicated that there were no significant relationships between the results for LPFW, TCW, and WiN– the three AC tasks identified by Bellis (2003). However, PhR was significantly related to both TCW and WiN. A more complete analysis was made in the attempt to predict PhR using multiple linear regression with the data from all three tasks. The overall ability to predict PhR using these three tasks was highly significant [F (3, 49) = 8.548, p = .000]. The partial correlations indicate the contribution of each factor above all others. The partial correlations revealed that only TCW [t= 3.863, p = .000] contributed significantly to the prediction. When WiN was considered in the pair-wise comparisons, it's correlation with

PhR was significant. However, in the multiple linear regression analysis, its contribution above all others was not significant [t = 1.745, p = .088]. As with the pair-wise correlation, the results of the multiple linear regression analysis for LPFW did not contribute significantly to the prediction of PhR [t = 1.867, p = .068].

V. DISCUSSION

The purpose of the present study was to determine the empirical relationships among tasks considered to measure AC. The results for the three tasks considered a part of AC (LPFW, TCW, and WiN) were not significantly correlated. These findings provide evidence that there are at least three components of AC that are independent of each other. The abilities associated with these tasks have been described as spectral reconstruction (LPFW), temporal resolution (TCW) and auditory induction (WiN). The terms used to describe these abilities represent a preliminary effort at labeling. They may be revised in the future, and other abilities may be included in the concept of AC. Since these abilities have been identified as independent of each other, no one task associated with these abilities can comprehensively be used to measure AC. Rather, these tasks represent the distinct abilities that compose the concept of AC, and each contributes to its occurrence in a distinct way.

Although not previously thought of as an AC task, PhR has been considered as an appropriate measure of AC (Bellis 2005). Warren's original view was that PhR with sentence-length stimuli is an auditory induction task. However, the results of the present investigation using multiple linear regression analysis provide evidence that, in the minimum context PhRW task, AC is accomplished primarily through temporal resolution. Further investigation will be needed to determine if all PhR is best characterized as requiring temporal resolution or auditory induction abilities.

AC has been considered to be an important ability in everyday life. Listeners who receive partial auditory information are able to understand an entire message. AC ability may also be used in conjunction with visual ability. In the present study, AC was examined to obtain normative data using very specific tasks and listeners. For each task, speech context was kept to a minimum. The attempt was made to avoid cognitive differences by using listeners who were college students with no reported learning or processing problems. Age differences and gender differences were not studied. Most importantly, listeners with AC problems were not studied. Further research is needed to determine how the independent components of AC are related in populations with auditory processing disorders, and how normal and disordered populations are related in regard to these concepts.

Despite the fact that AC was only studied using normal hearing listeners and stimuli of minimal context, the results add description to the understanding of the concept of AC in a general sense. The description is the identification of three distinct components that were not related in terms of performance. To understand AC capability, it appears that no single test provides comprehensive assessment of the auditory functions that enable AC to occur. Thus, comprehensive assessment of AC requires the measurement of several abilities. The present research opens a line of investigation by providing an initial empirical identification of independent components believed responsible for AC and a method for identifying the contributions of components.

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APPENDICES

APPENDIX A. Instructions and Word Lists for the WiN

Read aloud to each participant:

You will hear a series of 50 words in the presence of background noise. I want you to listen to each word carefully and repeat it. Listen carefully because I will not be able to repeat any of the words.

List 4-D (1)

1. they
2. yes
3. leave
4. pale
5. bread
6. eyes
7. toy
8. yet
9. near
10. save
11. clothes
12. few
13. all
14. my
15. so
16. am
17. tin
18. shoe
19. can
20. darn
21. men
22. ear
23. through
24. ought
25. wood

List 4-D (2)

1. at
2. dust
3. our
4. in
5. tea
6. will
7. art
8. cook
9. his
10. go
11. stiff
12. where
13. chin
14. who
15. net
16. hang
17. aid
18. nuts
19. arm
20. why
21. than
22. of
23. jump
24. dolls
25. bee

APPENDIX B**.** Instructions and Word List for the TCW

Read aloud to each participant:

You will hear a series of 50 words that have been compressed in time. I want you to listen carefully and repeat each word as you hear it. If you do not understand a word, make a guess. I will not be able to repeat any of the words.

Each word was preceded by the carrier phrase “Say the word”.

1. pool
2. knock
3. ditch
4. road-rode
5. chat
6. page
7. wag
8. hole-whole
9. love
10. jar
11. chalk
12. nag
13. red
14. ring
15. sheep
16. pad
17. jail
18. burn
19. base
20. half
21. read-reed
22. perch
23. choice
24. tip
25. lose
26. puff
27. peg
28. bone
29. thumb
30. keg
31. yes
32. third
33. long
34. should
35. gaze
36. check
37. lid
38. beg
39. tough
40. wife
41. shawl
42. rag
43. fail
44. sell
45. king
46. rot
47. hit
48. boat
49. tool
50. keep

APPENDIX C. Instructions and Word List for the LPFW

Read aloud to each participant:

You will hear a series of 50 words that have been reduced in the pitch of their sound. I want you to listen carefully and repeat each word as you hear it. If you do not understand a word, make a guess. I will not be able to repeat any of the words.

1. youth
2. mouse
3. lid
4. pole
5. beg
6. hire
7. pearl
8. when
9. soup
10. pain
11. shall
12. cab
13. tell
14. note
15. germ
16. base
17. talk
18. walk
19. luck
20. road-rode
21. name
22. sheep
23. rush
24. chat
25. thin
26. wire
27. cool
28. ditch
29. bar
30. mess
31. dodge
32. cheek
33. five
34. team
35. search
36. seize
37. gun
38. cause
39. good
40. void
41. phone
42. half
43. date
44. mop
45. jug
46. late
47. ring
48. life
49. rat
50. hit

APPENDIX D. Instructions and Word List for the PhRW

Read aloud to each participant:

You will hear a series of 50 words that have an inserted cough. I want you to listen carefully to each word and repeat it (without the cough) as you hear it. If you are not sure what was said, take a guess. Listen carefully because I cannot repeat any item.

1. blackboard
2. sunshine
3. playpen
4. greyhound
5. downtown
6. northwest
7. necktie
8. drawbridge
9. grandson
10. bedroom
11. hopscotch
12. duckpond
13. drugstore
14. workshop
15. sunset
16. mousetrap
17. schoolroom
18. railroad
19. highchair
20. footstool
21. airplane
22. toothbrush
23. playground
24. outside
25. mushrom
26. meatball
27. jacknife
28. iceburg
29. hotdog
30. football
31. ashtray
32. scarecrow
33. hothouse
34. baseball
35. armchair
36. doorstep
37. stairway
38. jumprope
39. hairbrush
40. farewell
41. cupcake
42. rainbow
43. pancake
44. headlight
45. doorbell
46. birthday
47. bathtub
48. playmate
49. icecream
50. oatmeal

Red letters indicate the deleted phonemic segment that was replaced with a 200ms cough.

APPENDIX E. Informed Consent

Consent Form to Participate in the Following Project:
"A Comparison of Auditory Closure Tests and the Accuracy of a Phonemic Restoration Task in Young Adult Normal Hearing Listeners: Examining the Relationship between Auditory Closure and Accuracy of Phonemic Restoration"

You are being asked to participate in a study of speech perception. The goal of this study is to determine how individuals with normal hearing perceive speech.

Procedures

If you take part in this study, you will listen to a series of word lists that have been altered. The words will be presented at loudness levels that represent comfortable conversational speech through one earphone in a sound-treated booth. You will be asked to repeat words that you hear. Completion of this experiment will take approximately one hour.

Potential risks or discomfort

There are no risks associated with participation in this study.

Benefits

The purpose of this research is to gain a better understanding of speech perception and auditory processing. You may receive extra-credit for course work for your participation in this study.

Assurance of confidentiality

Information learned about you will be kept confidential. When referring to data collected from you in presentations or publications, we will use a code number and will not use your name.

Alternatives

You do not have to take part in this study if you do not want to. Your participation or non-participation in this project will in no way affect your academic standing in the Department of Audiology and Speech Pathology or Psychology. This form will be stored in a locked file cabinet in 544 South Stadium Hall at the University of Tennessee, Knoxville for three years.

Right to withdraw

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

Right to inquire

If you have any questions about this study, you can write or call the researchers listed at the bottom of this form.

Authorization

I have read this form in its entirety and feel I understand the possible risks, discomforts, and benefits of this study. I agree to participate in this study. I acknowledge that I have received a copy of this consent form.

____________________________________ ___________

Participant's signature Date

Investigator's assurance

The individuals whose names appear below are responsible for carrying out this research program. They will assure that all questions about this research program are answered to the best of their abilities. They will assure that you are informed of any changes in the procedures or the risks and benefits if any should occur during or after the course of this study. They will assure that all information remains confidential.

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APPENDIX F. Listener Responses in Percent Correct (Root Arcsine Transformation Units of Percent Correct Scores)

Participant	Age	LPFW	TCW	WiN	PhRW
1	22	70 (99)	86 (119)	84 (116)	90 (125)
2	21	62 (91)	86 (119)	64 (93)	72 (101)
3	22	68 (97)	82 (113)	84 (116)	86 (119)
4	23	50 (79)	82 (113)	74 (104)	76 (106)
5	21	90 (125)	56 (85)	56 (85)	52 (81)
6	22	72 (101)	68 (97)	72 (101)	64 (93)
7	22	60 (89)	84 (116)	84 (116)	88 (122)
8	21	68 (97)	72 (101)	72 (101)	82 (113)
9	21	74 (104)	78 (108)	78 (108)	88 (122)
10	28	76 (106)	86 (119)	80 (111)	80 (111)
11	20	68 (97)	80 (111)	74 (104)	78 (108)
12	31	86 (119)	78 (108)	76 (106)	94 (132)
13	22	70 (99)	84 (116)	76 (106)	84 (116)
14	22	88 (122)	80 (111)	74 (104)	66 (95)
15	20	82 (113)	82 (113)	86 (119)	72 (101)
17	20	66 (95)	86 (119)	66 (95)	82 (113)
18	22	90 (125)	90 (125)	84 (116)	86 (119)
19	24	54 (83)	78 (108)	76 (106)	68 (97)
20	21	78 (108)	80 (111)	78 (108)	90 (125)
21	21	76 (106)	72 (101)	80 (111)	74 (104)
23	24	66 (95)	92 (128)	70 (99)	86 (119)
25	20	72 (101)	74 (104)	78 (108)	74 (104)
27	23	70 (99)	74 (104)	66 (95)	72 (101)
28	21	72 (101)	78 (108)	82 (113)	70 (99)
29	21	60 (89)	76 (106)	90 (125)	72 (101)
30	19	68 (97)	68 (97)	74 (104)	72 (101)
31	22	66 (95)	90 (125)	84 (116)	90 (125)
32	30	66 (95)	88 (122)	80 (111)	76 (106)
34	20	76 (106)	72 (101)	76 (106)	74 (104)
35	22	64 (93)	88 (122)	72 (101)	82 (113)
36	22	64 (93)	76 (106)	78 (108)	72 (101)
37	20	62 (91)	78 (108)	74 (104)	74 (104)
38	22	56 (85)	86 (119)	72 (101)	78 (108)
39	21	70 (99)	80 (111)	80 (111)	74 (104)
40	18	64 (93)	76 (106)	88 (122)	72 (101)
41	22	72 (101)	84 (116)	66 (95)	86 (119)
42	24	72 (101)	84 (116)	74 (104)	74 (104)
43	22	72 (101)	88 (122)	66 (95)	78 (108)
44	19	48 (77)	62 (91)	70 (99)	64 (93)
45	20	58 (87)	82 (113)	70 (99)	72 (101)
46	21	70 (99)	74 (104)	70 (99)	76 (106)
47	24	64 (93)	80 (111)	78 (108)	78 (108)
48	20	54 (83)	82 (113)	82 (113)	78 (108)
49	23	62 (91)	72 (101)	82 (113)	74 (104)
50	22	62 (91)	58 (87)	62 (91)	76 (106)
51	22	54 (83)	88 (122)	70 (99)	70 (99)
52	24	46 (75)	86 (119)	84 (116)	72 (101)
53	21	44 (73)	80 (111)	44 (73)	64 (93)
54	21	54 (83)	82 (113)	70 (99)	66 (95)
55	21	62 (91)	74 (104)	66 (95)	70 (99)

VITA

Steven G. Madix is a native of North Louisiana. He received his bachelors and masters degrees from Louisiana Tech University. He is married with two sons, David Keith and John Louis. In his spare time, he enjoys any outdoor activity with family and friends. Upon completion of his Doctorate, Mr. Madix will join the Department of Speech faculty at Louisiana Tech University in Ruston, Louisiana as Assistant Professor.