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Interactions between Cognition and Hearing Aid Compression Release Time: Effects of Linguistic Context of Speech Test Materials on Speech-In-Noise Performance

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INTERACTIONS BETWEEN COGNITION AND HEARING AID COMPRESSION RELEASE TIME: EFFECTS OF LINGUISTIC CONTEXT OF SPEECH TEST MATERIALS ON SPEECH-IN-NOISE PERFORMANCE

by

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Dedication

To my parents Xiaoming Xu and Junling Zhu, who light my path

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ABSTRACT

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Difference in speech recognition performance with short and long release time processing has been noted in previous research. Recent research has established a connection between hearing aid users' cognitive abilities and release time. Researchers hope to use cognitive ability as a predictor of release time selection. The results from these previous studies have been contradictory. Some researchers hypothesized that linguistic context of speech recognition test materials was one of the factors that accounted for the inconsistency. The goal of the present study was to examine the relationship between hearing aid users' cognitive abilities and their aided speech recognition performance with short and long release time using speech recognition tests with different amounts of linguistic context.

Thirty-four experienced hearing aid users participated in the present study. Their cognitive abilities were quantified using a reading span test. Digital behind-the-ear style hearing aids with adjustable release time settings were bilaterally fitted to the participants. Their aided speech recognition performance was evaluated using three tests with different amounts of linguistic context: the Word-In-Noise (WIN) test, the American Four Alternative Auditory Feature (AFAAF) test, and the Bamford-Kowal-Bench Speech-In-Noise (BKB-SIN) test.

The present study replicated the results of an earlier study using an equivalent speech recognition test. The results from the present study also showed that hearing aid users with high cognitive abilities performed better on the AFAAF and the BKB-SIN compared to those with low cognitive abilities when using short release time processing. Results showed that none of the speech recognition tests produced significantly different performance between the short and the long release times for either cognitive group. This finding did not support the hypothesis of the effect of linguistic context on aided speech recognition performance with different release time settings. Results from the present study suggest that cognitive ability might not be important in prescribing release time.

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Introduction

Digital, wide dynamic range compression (WDRC) hearing aids, which provide nonlinear amplification, have been increasingly used nowadays. Release time is an important parameter of the nonlinear compression function, which determines how quickly the compressor reacts to a decrease in input sound level. Release time varies from milliseconds to seconds. It is generally accepted that release times can be considered short when they are less than 100 milliseconds and long when they are greater than 500 milliseconds. With different release time settings, the temporal envelopes of amplified sounds, especially speech signals, can vary drastically. With inappropriate release time settings, a hearing aid user’s speech understanding performance may be compromised resulting in poor hearing aid benefit and satisfaction. A question naturally arises: what release time setting should be used, a short one or a long one? Unfortunately, to date no standardized strategy or protocol for prescribing release time exists. Audiologists and hearing aid specialists often use the default release time setting that is recommended by the hearing aid’s manufacturer. With this method, not all hearing aid users are satisfied.

The importance of release time selection has been well acknowledged and a number of studies have sought to determine the overall superiority of either short or long release time. Such previous studies have investigated the advantages and disadvantages of different release times under a variety of test conditions. Findings have been inconclusive and numerous factors could possibly account for the discrepant results.

More recent research has examined the role of cognition in determining release time superiority (Cox & Xu, 2010; Foo, Rudner, Rönnberg, & Lunner, 2007; Gatehouse, Naylor, & Elberling, 2003; Lunner & Sunderwall-Thoren, 2007). Here too, inconsistent results have been obtained. Some of the studies have concluded that listeners with greater cognitive abilities perform better with short release times when tested in modulated background noises, while listeners with poorer cognitive abilities perform better with long release times when tested in unmodulated background noises (Gatehouse et al., 2003; Lunner & Sunderwall-Thoren, 2007). Others have found that release time is crucial only for hearing aid users with low cognitive abilities (Cox & Xu, 2010; Foo et al., 2007). A number of factors could potentially underlie this inconsistency. Three of these factors in particular deserve further investigation.

The first factor is the measurement of cognitive performance. A variety of methods has been used to evaluate hearing aid users' cognitive abilities, such as the visual letter monitoring test (Gatehouse et al., 2003) and the letter-number sequencing test (Weschler, 1997). Different methods might measure different dimensions of cognition, so that the categorization of low and high cognitive performance differs substantially across tests. Working memory is one of the dimensions that is very closely related to speech recognition. It can both store recently received speech information and provide a computational mental workspace. The recently stored speech information can be integrated with relevant information stored in long-term memory and this supplementary information can be utilized to assist in understanding speech. The capacity of working memory can be measured with a variety of tests. Akeroyd (2008) reviewed all pertinent studies in the field of audiology and suggested that reading span tasks are probably the most-effective tasks for examining working memory capacity.

A second factor is linguistic context of speech test materials. Different speech recognition test materials have been used in studies for assessing release time superiority. Some studies have used sentence tests (e.g., Foo et al., 2007), whereas some have used word-based tests (e.g., Gatehouse et al., 2003). Different test materials provide different amounts of linguistic context. There is evidence that the ability to make use of the non-acoustic cues (e.g., the context of a sentence) in assisting speech understanding is associated, at least to some extent, with hearing aid users' working memory capacity (Pichora-Fuller & Singh, 2006). The type of speech recognition test material with regard to linguistic context which is the most sensitive for assessing release time superiority, is still unknown.

A third factor is the procedure for measuring speech recognition performance. Procedures used in previous work for measuring aided speech recognition performance in noise have differed: some have used adaptive procedures while some were with fixed signal-to-noise ratio (SNR) procedures. Differences in measurement procedure could dramatically influence aided speech recognition in noise. Naylor and Johannesson (2009) suggested that the most valid method is to measure speech recognition performance in noise with a number of appropriately spaced, fixed SNRs. One way of evaluating such a recognition performance measure is using a psychometric function, which provides an overall view of the recognition performance as a function of SNR. The SNR that corresponds to a given behavioral performance level (e.g., 50% correct) is a parameter for evaluating speech recognition performance.

With consideration of the three factors as noted above, the current study continued to examine the relationship between cognitive abilities of listeners with hearing impairment and their aided speech understanding performance in noise with varying release times. In this study, each listener's cognitive ability was measured with a reading span test. Aided speech recognition performance was evaluated in several predetermined SNR conditions with three speech recognition test materials differing in the amount of linguistic context. Interactions between cognitive abilities and release time were assessed for each speech recognition test. The following questions were answered:

1. What is the relationship between cognitive abilities and aided speech recognition performance in noise with short and long release times when high context test materials are used?

2. What is the relationship between cognitive abilities and aided speech recognition performance in noise with short and long release times when low context test materials are used?

Chapter 2

Review of the Literature

The central goal of this study is to investigate how a hearing aid user's cognitive abilities relate to the superiority of compression release time. This chapter reviews the literature relevant to the research purpose of this dissertation project: (1) release time, (2) working memory and reading span tasks, (3) speech recognition performance, and (4) psychometric functions.

Release Time

In this section, we begin with a short tutorial on compression release time, after which we turn our focus to the superiority of long or short release times, paying particular attention to the interaction with the cognitive abilities of hearing aid wearers.

Introduction of Compression Time Constants

The time constant of a wide dynamic range compression (WDRC) hearing aid is one of the basic parameters which can dramatically affect the dynamic behavior of the device and therefore impact acoustic signal processing and speech perception. It is composed of an attack time and a release time. The attack time is used to quantify how fast a hearing aid compressor reacts to an input sound signal with increasing intensity. The release time is defined as the time taken for the output signal to increase to within 4 dB of its final value following a decrease in input level from 90 to 55 dB SPL (Dillon, 2001). It is generally agreed that the attack time should be short (typically less than 50 milliseconds) to allow immediate reaction to incoming sounds, though some manufactures also provide options for a long attack time interval. However, the release time varies from milliseconds to seconds, and yet there is no consensus regarding its setting. Therefore, debates about the compression time constant fall on the release time.

Characteristics of Release Time

So far, there still is no consensus regarding the definition of short and long release times. However, it is generally accepted that release times can be considered short when they are less than 100 milliseconds, and long when they are greater than 500 milliseconds. Some basic aspects of the advantages and disadvantages in using either a short or a long release time are well acknowledged. However, it should be noted that the advantages and disadvantages discussed here do not exclusively result from the release time itself, but also result from a more complex interaction with other aspects of devices (e.g., compression ratio), acoustical conditions (e.g., noise background), and sometimes hearing aid wearers (e.g., cognitive abilities). The advantages and disadvantages for either type of release time were thoroughly discussed in Moore (2008) and are briefly summarized in the following paragraphs.

A short release time can react very quickly to changes in sound intensity. It has been claimed that it allows the hearing aid to provide greater gain to soft sounds, which results in an improvement in audibility of soft consonants and thereby, to some extent, restores loudness perception to “normal.” Also, when using multi-channel hearing aids, short release time processing can compensate for frequency-dependent changes and works well for listeners who are hearing-impaired with loudness recruitment (Villchur, 2008). In addition, short release time processing allows softer sounds immediately following intense sounds to be audible. Similarly, short release time processing provides good results when two voices alternate with very different levels.

In spite of the merits of short release time processing, some potential drawbacks are also evident. By providing more gain to softer sounds, short-term amplitude contrasts of a speech signal (e.g., consonant-to-vowel ratio) will be altered and the temporal pattern of the speech signal will be distorted. As a consequence, naturalness of the processed speech signal will be compromised. Another frequently claimed disadvantage in using short release time processing is the perceived distraction with background noise during the pauses of ongoing speech. A hearing aid with a short release time will provide greater gain to low-intensity background noise during the pauses of ongoing speech and hence deteriorate listening comfort.

A compressor with long release time processing maintains gain for a longer period of time compared to a compressor with short release time processing. Thus, the internal intensity difference of a speech signal can be largely preserved and minimum perceived distortion can be achieved. Consequently, signals processed with a long release time could be more natural and the listening comfort of hearing aid wearers could be increased. By the same token, in a noisy environment, larger gain will not be applied to the relatively low level background noise during the pauses of speech, and consequently, listening comfort could be improved.

Adverse effects of long release time processing are also substantial. First, a hearing aid compressor with a long release time might not be very helpful when multiple speech signals with different sound levels alternate. Second, available speech cues in a modulated background masker may not receive enough amplification with long release time processing, so that speech understanding ability in such a condition will be diminished. Third, when an intense sound precedes a softer sound, the gain applied to the intense sound will be decreased due to the nonlinear amplification algorithm. Such lower amount of gain will be still applied to the succeeding softer sounds because of a long compression release period, which might result in inaudibility. By the same token, in the real-world, many hearing aid users who wear hearing aids with long release times may often experience a silent moment when they leave from a noisy environment to a quieter environment. This is because a low gain will be applied when staying in the noisy environment, and it will take a moment for the hearing aid amplifier to provide appropriate gain after leaving the noisy environment owing to the long release time processing.

Superiority of Short versus Long Release Times

Despite the fact that numerous characteristics of both short and long release times have been identified, debates still remain on whether one type of release time setting is superior to the other. Further questions are also raised regarding which release time setting is appropriate for a given hearing aid wearer and whether there is a standard method that can assist audiologists in release time selection. A number of studies have been undertaken in evaluating different release time settings for the sake of looking for such superiority. Results generally did not show a significant difference between short and long release times (Bentler & Nelson, 1997; Gilbert, Akeroyd, & Gatehouse, 2008; Jenstad & Souza, 2005; Moore, Stainsby, Alcantara, & Kuhnel, 2004; Muller, Harris, & Ellison, 2004; Novick, Bentler, Dittberner, & Flamme, 2001; Shi & Doherty, 2008; van Toor & Verschuure, 2002).

It is worth noting that the aforementioned studies, which reported no significant difference between short and long release times, were mostly based on speech recognition performance. However, some other studies, which evaluated perceived sound quality, clarity, and pleasantness, reported superiority of one type of release time to the other (Hansen, 2002; Neuman, Bakke, Mackersie, Hellman, & Levitt, 1995, 1998).

Neuman et al. (1995) studied the influence of release time on perceived quality of processed sounds. A simulated hearing aid was fitted on 20 subjects with the NAL-R prescription method. Nine hearing aid settings comprised three compression ratios (1.5, 2, and 3) and three release times (60, 200, 1000 milliseconds). Continuous discourse was evaluated in three different background noises in a laboratory setting (ventilation noise, urban apartment noise, and cafeteria noise) with a round robin format paired-comparison method. Results revealed that release times interacted with noise. They suggested that short release times worked better for quieter environments, while long release times worked better for noisier environments. In 1998, Neuman and colleagues extended their earlier study to further examine how manipulating release time and compression ratio impacted different aspects of the perceived sound quality. Clarity, pleasantness, background noise, loudness, and overall impression of speech-in-noise were rated by all test subjects via a 10-point Likert scale. A higher score indicated better perception. Results showed that higher ratings were given to long release time processing on clarity, pleasantness, and overall impression, whereas higher ratings were given to short release time processing on background noise and loudness.

Another study was conducted by Hansen (2002) to determine the influence of the compression time constants in a multi-channel compression hearing aid. One purpose of the study was to investigate the interaction of release time, compression threshold, and compression ratio. The parameter combinations (Attack time [millisecond] /Release time [millisecond] /Compression threshold [dB] /Compression ratio) were 1/40/20/2.1, 1/40/50/3, 1/40/50/2.1, and 1/4000/20/2.1. Three stimuli were incorporated in the rating (everyday situation, binaural recordings of noise mixed with speech material, and noise only signals without speech and of stereo music signals). The subjective perceived sound quality and speech intelligibility in realistic binaural sound environments were evaluated with a round-robin paired-comparison procedure. A 7-point scale from -3 to 3 was used for rating. Results showed that all subjects showed a significant preference for the longest release time (4,000 milliseconds) over the two shorter release times pertaining to quality and intelligibility. Moreover, the subjects who were hearing-impaired showed a significant preference for the hearing aid setting with a long release time (4,000 milliseconds) and a low compression threshold (20 dB SPL). Also, larger inter-individual difference was observed among all subjects with regard to the perceived sound quality of musical and non-speech signals.

According to the cited studies, overall superiority for either type of release time processing is still unclear. Nevertheless, some studies using subjective rating indicate that the release time benefits and preference actually exist. Moreover, a very recent study which measured the release time preference in the real world based on interview data showed that hearing aid users did appear to have clear release time preference in the real world; this observation was further supported by subjective measures with three standardized questionnaires (Cox & Xu, 2010). Despite the fact that researchers have failed to develop a sensitive test battery for determining the superiority of short versus long release time processing, the differences between them are real and substantial. Thus, researchers are motivated to investigate in a broader domain and seek other possible factors which can assist in explaining release time preference and establishing methods for release time prescription.

The role of cognition. Hearing aids are widely used to compensate for age-related hearing loss. Amplification provided by hearing aids can somewhat restore audibility for aged listeners with hearing loss and ease the communication process. However, other than sensory decline induced by aging, presbycusic listeners also experience age-related cognitive degradation. Research shows that age-related cognitive changes are one of the important factors that contribute to the speech processing difficulties in elderly listeners (Schneider & Pichora-Fuller, 2000) and this factor is substantially associated with aided speech recognition (Gatehouse, Naylor, & Elberling, 2006b; Lunner, 2003). It is encouraging that investigations on the association between speech recognition and cognition have opened a new door to help researchers better understand the mechanism of speech perception and comprehension in the auditory and cognitive systems, as well as assisting in developing better strategies in hearing aid prescription.

Researchers have hypothesized that cognitive systems may interact with different signal processing characteristics. Compression release time is one of the hearing aid parameters which can have considerable impact on signal processing. Recently, great interest has developed in looking at the relationship between cognitive abilities and performance with short and long release time processing (Cox & Xu, 2010; Foo et al., 2007; Gatehouse et al., 2003, 2006b; Lunner & Sunderwall-Thoren, 2007; Rudner, Foo, Rönnberg, & Lunner, 2009). Researchers sought to determine whether cognitive performance could be used to assist in determining release time superiority and prescribing hearing aids. Among these studies, aided speech recognition performance and cognitive abilities were measured in different ways and results were, as yet, inconclusive.

A seminal paper by Gatehouse et al. (2003) explored the interaction between the audiometric and cognitive characteristics of listeners and the test conditions under which speech recognition performance were evaluated. One of the research questions was to investigate the extent to which cognitive capabilities of listeners who are hearing-impaired influence their aided speech recognition performance when using nonlinear hearing aids with different release time settings (40 msec versus 640 msec). A

10-week acclimatization period was employed for each release time setting. Gatehouse and colleagues concluded that listeners with greater cognitive abilities performed better with short release times when they were tested in modulated background noises, while listeners with poorer cognitive abilities performed better with long release times when they were tested in unmodulated background noises.

The data obtained in Gatehouse et al. (2003) were incorporated into a subsequent report aimed at studying factors of determining candidacy for benefits offered by hearing aids (Gatehouse et al., 2006b). Candidacy dimensions included hearing thresholds, uncomfortable listening levels, masking noise characteristics, cognitive capacity, self-report, and acoustic measures of auditory ecology, etc. Nine predictor factors (hearing loss, slope and dynamic range, upward spread of masking, effect of spectral and temporal smearing, cognitive function, auditory lifestyle and demand, overall dosimeter distribution, dosimeter between-frame variability, and dosimeter within-frame variability) were derived from the collected data based on a set of principle component analyses. Four benefit factors (listening comfort, satisfaction, reported intelligibility, and speech test benefit) derived from Gatehouse et al. (2006a) were correlated with the nine predictor factors for each hearing aid setting. Results stressed the important role of cognitive function in relation to speech understanding benefit with short and long release times.

The pattern found in Gatehouse et al. (2003) shed light on the important role of cognitive function in optimizing the benefit of using short or long release time processing. Some studies tried to generalize this pattern in another language and with other test methods. Lunner and Sundewall-Thoren (2007) basically replicated several experiments described in Gatehouse et al. (2003), with all test materials in Danish. Twenty-three hearing aid wearers were tested under a short (40 msec) and a long (640 msec) release time setting. Data from this study endorsed what had been found in Gatehouse et al. (2003).

Foo et al. (2007) measured aided speech recognition performance of 32 elderly adults comparing a short (40 msec) with a long release time (640 msec) compression processing in modulated and unmodulated masking noises. All test materials were in Swedish. Hagerman sentences (Hagerman & Kinnefors, 1995) and Swedish Hearing in Noise test (Swedish-HINT; Hällgren, Larsby, & Arlinger, 2006) sentences were used as speech stimuli. Cognitive function was tested with a reading span task and a visual letter-monitoring task. No acclimatization was allowed after hearing aid fitting. Results revealed that listeners with low reading span scores had better aided speech recognition performance with long release time processing when tested with Hagerman sentences, regardless of masker modulation. On the other hand, listeners with low scores on the visual letter-monitoring task had better aided speech recognition performance with short release time processing when tested with Swedish-HINT in both maskers. This study showed a different pattern compared to previous findings reported by Gatehouse et al. (2003, 2006b) and Lunner and Sundewall-Thoren (2007).

Considering the inconsistencies of the previous studies, Rudner et al. (2009) did a follow-up study based on Foo et al. (2007), seeking more convincing evidence in determining the superiority of either type of release time under different test conditions. They tried to provide an explanation based on the “mismatch” hypothesis. Briefly, this hypothesis referred to how input auditory signals matched to the existing long-term phonological representation. Input signals that matched the long-term phonological representation could be recognized easily, otherwise, poor recognition performances might occur. It is assumed that new phonological representation could be developed after a period of acclimatization after hearing aid fitting. The effect of acclimatization was considered by Rudner and colleagues for comparison to Foo et al. (2007), in which no acclimatization period was provided. The experimental design was very similar to Foo et al. (2007). Thirty-one experienced hearing aid wearers participated in this study. The short and the long release time settings were 40 milliseconds and 640 milliseconds, respectively. Instead of testing the subjects right after hearing aid fitting, a nine-week acclimatization period was incorporated. About half of the subjects only used the short release time and another half only used the long release time during the nine-week period. In the aided speech tests, each listener was tested with both release time settings no matter which one he or she had been acclimatized to. Results indicated that aided speech-recognition performance in noise was generally improved after the added acclimatization period. However, the post-acclimatization aided performance was not significantly affected by the release time settings they used in the acclimatization period.

An interaction between cognitive abilities (quantified by a reading span test) and release time settings was found when using the Swedish-HINT. However, Rudner and colleagues did not compare the two release time settings for each cognitive performance group. Instead, they compared the two cognitive performance groups for each release time setting. They found that listeners with high cognitive abilities did significantly better than listeners with low cognitive abilities when using the long release time setting.

A more recent study by Cox and Xu (2010) evaluated cognitive function in a comprehensive way, from which stronger evidence of the association between cognitive function and speech understanding with short and long release times were expected to be detected. In this study, short and long release time settings were 40 milliseconds and 640 milliseconds, respectively. Aided speech recognition performance in noise was assessed using the speech pattern contrast (SPAC) test (Boothroyd, 1985) and the Bamford-Kowal-Bench Speech-In-Noise (BKB-SIN) test (Etymotic Research, 1985). A composite cognitive score was calculated for each participant by combining the scores from the visual letter monitoring (VLM) test (Gatehouse et al., 2003), the Wisconsin card sorting test (WCST) (Heaton, 1981), and the letter-number sequencing (LNS) test (Weschler, 1997). The results of this study were contradictory to the results reported in Gatehouse et al. (2003) and Lunner and Sunderwall-Thoren (2007), but partially consistent with the ones reported in Foo et al. (2007). Cox and Xu found that listeners with low cognitive scores performed significantly better with short release time processing when aided speech recognition performance was tested with the SPAC.

However, the two release times were not significantly different from each other when the BKB-SIN was used to evaluate aided speech recognition performance. It was also suggested that release time processing is more important for listeners with lower cognitive abilities than for those with higher cognitive abilities.

Results from the aforementioned studies focusing on the relationship between cognitive ability and release time are summarized in Table 1. As shown in this table, for each study, speech recognition test, cognitive test, cognitive performance, and release times that produced better speech recognition performance for each cognitive performance group are listed. Among the reported results, some are statistically significant findings while others are non-significant descriptive conclusions. For example, in Lunner and Sunderwall-Thoren (2007), the Dantale II was used as the measure of aided speech recognition performance; the VLM test was used to assess participants' cognitive abilities. Based on the VLM scores, the participants were categorized into low and high cognitive performance groups. The release time that produced better speech recognition performance for each of the two groups was indicated. Specifically, the low cognitive performance group performed significantly better on the speech recognition test with long release time processing than with short release time processing. Whereas, the high cognitive performance group performed better with short release time processing than with long release time processing, but this finding was not statistically significant.

Table 1

A Summary of the Results Reported in Previous Studies Focusing on the Relationship Between Cognitive Ability and Aided Speech Recognition Performance with Short and Long Release Time Processing.

	Speech Recognition Test	Cognitive Test	Cognitive Performance	RT that produced better speech recognition performance
Gatehouse et al. (2003)	Four Alternative Auditory Feature Test	Visual Letter Monitoring	Low	Long
			High	Short
Lunner & Sunderwall-Thoren (2007)	Dantale II	Visual Letter Monitoring	Low	Long*
			High	Short
Foo et al. (2007)	Swedish-Hearing In Noise Test	Visual Letter Monitoring	Low	Short*
			High	#
		Reading span		#
	Hagerman Sentences	Visual Letter Monitoring		#
		Reading span	Low	Long*
			High	#
Cox & Xu (2010)	Speech Pattern Contrast Test	Composite cognitive scores	Low	Short*
			High	Long

* Statistically significant.

Non-significant, no results reported.

The reviewed literature provides an informative background of current research about release time in compression hearing aids. Several aspects with regard to both rationales for investigating release time superiority and measurement methods caught our attention albeit with varied results. First, cognitive performance of hearing aid users appears to be an influential factor. Its role in research seeking release time advantages has been stressed in many recent studies. Second, speech recognition tests used in the reviewed studies vary greatly in linguistic context. The relationship between linguistic contexts of speech test materials and aided speech recognition performance with different release times is unclear. Third, procedures used for measuring aided speech recognition performance in noise are different: some are with adaptive-SNR procedures while some are with fixed-SNR procedures. Naylor and Johannesson (2009) studied long-term input/output SNRs in compression hearing aids and found that speech recognition performance in noise could be different when listeners were tested with adaptive and fixed-stimulus procedures. Therefore, they suggested that the most valid method is to measure speech recognition performance in noise with a number of appropriately spaced, fixed input SNRs. With this method, a listener’s speech recognition performance is measured under several SNR conditions. One way of evaluating such a recognition performance measure is using a psychometric function. With this method, performance on different speech recognition measures under the same SNR conditions can be effectively compared. The comparison is based not only on performance in each SNR condition but also on the rate of performance improvement as SNR increases.

Based on the aforementioned concerns, we will continue reviewing three other relevant topics in the following sections: (a) cognitive function, especially working memory, (b) speech recognition, and (c) psychometric function.

Working Memory and Reading Span Tasks

In previous studies, researchers observed that the aspects of cognitive function that were closely associated with speech recognition performance were memory and cognitive processing (see Akeroyd, 2008). The two aspects are well represented by working memory (Baddeley & Hitch, 1974). Therefore, the review in this section about cognitive function is concentrating on the function of working memory and its measurement method, with a particular focus on reading span tasks.

Working Memory and Its Nature

Working memory is a theoretical construct within cognitive psychology. A well-known working memory model introduced by Baddeley and Hitch (1974) considers working memory to be one of the cognitive functions associated with short-term memory. This model proposes that working memory is composed of three parts: a central executive system, a phonological buffer, and a visual-spatial buffer. The phonological buffer and visual-spatial buffer are also considered as "slave systems," which are responsible for short-term maintenance of information. The central executive system, on the other hand, is responsible for the supervision of information integration and for coordinating the slave systems. Based on this model, two aspects of cognitive processing are working in parallel: temporary storage and information processing.

Relationship to Auditory Perception and Processing

Working memory is involved in a wide range of complex cognitive behaviors, such as comprehension, reasoning, and problem solving (Engle, 2002). A diverse set of research is now measuring the relationship between working memory capacity and other aspects of interest. Previous research found evidence that measures of cognitive ability, especially working memory capacity, were most effective in determining cognitive functions associated with speech recognition performance (Akeroyd, 2008).

Working memory correlates closely with auditory perception and processing. Auditory functioning basically consists of four phases: hearing, listening, comprehending, and communicating (Kiessling et al., 2003). Comprehending spoken language in every day situations requires more working memory than listening to short segments of speech and immediately recalling them. In order to comprehend spoken language, listeners not only have to identify individual speech sounds and words but also must integrate successively heard words, phrases, and sentences to arrive at a coherent and accurate representation of the message being communicated (Gordon, Daneman, & Schneider, 2009; Schneider, Daneman, Murphy, & Kwong-See, 2000). The temporal storage function of working memory allows auditory information to be accumulated, while the central executive system of working memory decodes and processes the accumulated information. Deterioration of either of these two functions will very likely compromise the efficiency and accuracy of communication and intellectual abilities. Particularly, older listeners often report more difficulty in understanding spoken language than would be expected given their degree of hearing loss (Martin & Jerger, 2005). Researchers observed that older listeners have poorer performance in both identifying and remembering words than their young counterparts possibly due to age-related cognitive decline (Pichora-Fuller, Schneider, & Daneman, 1995). Therefore, the mechanism of working memory makes cognitive processing crucial to the active and effortful activities of listening, comprehending, and communicating (Pichora-Fuller & Singh, 2006).

In addition to acoustic signals, the use of non-acoustic cues for understanding speech can be associated with working memory to some extent. According to research in speech understanding, there is a need for a working memory system to hold temporarily the phrases and clauses of sentences in order to determine the correct sentence meaning (Wingfield & Tun, 2007). Since working memory can both store recently received information and provide a computational mental workspace, the recently stored information can be manipulated and integrated with relevant information stored in long-term memory (Pichora-Fuller & Singh, 2006). Thus, non-acoustic cues, for example, the listener’s previous knowledge of the speech topic, provide additional information in understanding the received speech. These cognitive supplements can effectively reduce speech information processing load and compensate for insufficient auditory input due to adverse acoustic environments or peripheral auditory deficits. Therefore, it is reasonably expected that a larger working memory capacity allows better internal monitoring of received speech information to facilitate speech understanding.

Measurement of Working Memory Capacity and Reading Span Tasks

Working memory is generally considered to have finite capacity, and to measure its capacity is a way to quantify working memory. Working memory capacity designates differences in the ability to control attention to maintain information in an active, quickly retrievable state. Greater working memory capacity means that more items can be maintained as active, and has a greater ability to use attention to avoid distraction (Engle, 2002). Since working memory capacity is a multi-dimensional quantity (Baddeley & Hitch, 1974), it can be measured by a variety of tasks. Working memory span tasks are commonly used for measuring working memory capacity, for example, counting span tasks (Case, Kurland, & Goldberg, 1982), operation span tasks (Tuner & Engle, 1989), and reading span tasks (Daneman & Carpenter, 1980). Conway et al. (2005) did a comprehensive analysis of the reliability and validity of some working memory span tasks (counting span, operation span, and reading span tasks). Conway and colleagues concluded that these span tasks were all reliable and valid measures of working memory capacity. Among all available span tasks, the reading span task was the first task used to measure both storage and processing functions of working memory, as well as the relationship between working memory and higher order cognition (Daneman & Carpenter, 1980). Akeroyd (2008) reviewed a number of studies focusing on auditory related functions in association with working memory and concluded that the reading span task was probably the most effective task for examining working memory capacity.

There are a number of reading span tests available for use and they are derived based on the same idea from the very first reading span test developed by Daneman and Carpenter in 1980. Since this first test sets the foundation for measuring working memory capacity with reading span tasks, it is worth describing this test in detail. Daneman and Carpenter (1980) first developed the reading span test as a means of assessing people's ability to perform active processing of a stimulus while simultaneously storing other information in working memory. To administer this test, subjects read sentences aloud and verify the logical accuracy of the sentences, while trying to remember the last word of each sentence presented. There are five groups of sentences, each of which has three sets of sentences. The sets vary in size as follows: group one contains three sets of two sentences each; group two contains three sets of three sentences each; group three contains three sets of four sentences each; group four contains three sets of five sentences each; and group five contains three sets of six sentences each. Each sentence has 13 to 16 words. An example of a sentence is: "When at last his eyes opened, there was no gleam of triumph, no shade of anger." The sentence groups are presented in ascending order. That is to say, the reading span test will start from the three sets of two sentences each in group 1. The subject's tasks are (1) to judge the logical accuracy of each sentence right after reading it aloud and (2) recall the last word of each sentence at the completion of each set. Increasingly large set-sizes of sentences are presented until the subject fails to recall all three sets of a given group. The subject’s reading span is determined as the set size at which he or she could correctly recall two of the three sentence sets.

Speech Recognition

One of the direct impacts of hearing impairment is difficulty understanding speech, especially with competing background noise. Deterioration in auditory systems, both peripheral and central, and other relevant systems (e.g., cognitive system) can account for such negative impact. Thus, assessing speech recognition performance becomes an essential part of hearing evaluation, and speech recognition tests have been widely used in clinical audiology and hearing research.

Information Processing

Understanding speech is, in essence, one type of information processing. It relates to the factors of cognitive abilities, speed in auditory information processing, and phonological skills (Hallgren, Larsby, Lyxell, & Arlinger, 2005). Two of the major processing strategies, top-down and bottom-up processing, are heavily involved in processing auditory information, especially speech. The interaction between top-down and bottom-up processing allows humans to understand speech and communicate with each other. It is also worth noting that these two processing strategies are not limited to auditory information processing; rather, they have a broader application spectrum, such as reading and visual perception. Only the auditory information processing will be elaborated in this review.

Nakagawa, Shikano, and Tohkura (1995) gave an overview of the two processing strategies for human information processing and speech perception. Top-down processing is based on higher level information, such as previous knowledge and expectations. Bottom-up processing is based on peripheral information in which recognition is carried out according to the analytical results of data input into the peripheral systems. Debates have been carried on among speech perception theories about the involvement of both top-down and bottom-up processing strategies. No general consensus has been reached according to the existing speech perception theories. A thorough examination of these theories is beyond the scope of this review. However, a comparative summary of a number of speech perception theories commented that the acoustic information is primary as long as it is clear (bottom-up processing), otherwise, the clearest portion will be primary and top-down information will be applied to assist in speech understanding (Hawkins, 1999). This suggests that both top-down and bottom-up processing strategies are involved in speech communication but the extent of the involvement is determined by the nature of speech signals.

Massaro (1994) further delineated how linguistic contexts and speech signals come together to support speech perception. One of the general explanations is that linguistic contexts might simply provide an additional source of information that supplements the sensory information. In speech perception, syntactic and semantic context constraints in a sentence can influence the speech perception system to perceive some speech segments (e.g., words) without changing the sensory system. Thus, context-rich speech signals can be understood in challenging listening environments by using top-down strategies to compensate for the degraded sensory inputs. Stevens (2000) further suggested that isolated word recognition is mostly based on bottom-up processing, while top-down processing will be involved when recognizing words in running speech.

Effect of Linguistic Context

Since linguistic contexts play such an important role in speech recognition with regard to cognition, a review of the effect of linguistic context is necessary.

Speech recognition performance can be influenced by a variety of factors. One of the factors is the linguistic context of test material, which is critical but very likely to be ignored by researchers. Among the existing test materials, some are richer in context and the target words are highly predictable; whereas, others are lower in context and the target words are less likely or even impossible to be predicted. That is, though one or more target words in a contextually rich segment are not heard in a speech recognition test, listeners still might be able to predict the missing words by using the syntactic and semantic cues. Test materials with predictable words or phrases can facilitate and improve speech recognition performance to some extent. Such effect could be more pronounced when listeners are tested in adverse acoustic conditions in which more guessing is needed.

Debates on how linguistic contexts impact speech recognition performance have been carried on and context-related effects have been reported. Previous investigations suggest that a speech recognition test using sentences with substantial linguistic context provides extra non-acoustic cues when compared to a test that uses monosyllabic words. Therefore, tests using highly contextual sentences can improve speech understanding in noise for listeners with normal hearing (McArdle, Wilson, & Burks, 2005). However, speech recognition tests that utilize sentences do not necessarily have equal amounts of linguistic context. Different test materials, which use sentences with different amounts of linguistic context, also can dramatically influence speech understanding performance (Wilson, McArdle, & Smith, 2007).

Linguistic contexts are critical for older listeners, especially for those with hearing impairment. Pichora-Fuller et al. (1995) found that speech recognition performance in both high- and low context conditions was poorer for older listeners with normal hearing compared to younger listeners with identical hearing sensitivity, when they were evaluated under the same SNR conditions. Given this finding, comparing the difference between high- and low-context speech recognition performance, older listeners received significantly greater benefit from utilizing linguistic context than their younger counterparts. Furthermore, there is also evidence that older listeners can successfully use the contextual cues provided by the sentence to compensate for their sensory loss (Dubno, Ahlstrom, & Horwith, 2000; Pichora-Fuller, 2008; Pichora-Fuller et al., 1995).

In addition, the context-related effect is also speculated as a possible explanation of the inconsistency in measuring compression release time advantage. As discussed earlier, contradictory findings on seeking the relationship between cognitive abilities and release time superiority were observed. Cox and Xu (2010) measured aided speech recognition performance with the SPAC test and the BKB-SIN test. The former was a word recognition test with contextually low carrier sentences while the latter was a sentence test with contextually rich sentences. The results showed that there was an interaction between release time and cognitive scores when the SPAC test was used. Post hoc analyses revealed that the hearing aid users with lower cognitive scores performed significantly better with short release time processing than with long release time processing. However, PI functions drawn from the BKB-SIN scores showed that the performance of hearing aid users with lower cognitive scores was not substantially different between short and long release time processing. It is reasonable to speculate that the inconsistent analysis results in previous studies might be attributable, at least to some extent, to the fact that different speech perception test materials have different linguistic contexts. Such suspicion suggested that the impact of linguistic context or lack thereof could be particularly critical for listeners with low cognitive abilities (Cox & Xu, 2010).

Speech Recognition Tests

There are several different speech recognition tests that are available for testing in clinical audiology and hearing research. Speech recognition tests can be categorized in a variety of ways. In this section, test material, scoring strategy, test format, and test condition will be discussed.

Test material. Speech recognition tests can roughly be categorized into nonsense-syllable tests, word-based tests, sentence tests, and continuous discourse tests.

First, a nonsense-syllable test is used to examine the ability to identify speech sounds that are constructed with meaningless combinations of vowels and consonants. An example of a nonsense syllable test is the City University of New York Nonsense Syllable Test (CUNY-NST), whose test materials are meaningless consonant-vowel (CV) and vowel-consonant (VC) syllables (Resnick, Dubno, Hoffnung, & Levitt, 1975). Second, a word-based test examines the ability of identifying syllables in a meaningful word context. The test words could be monosyllabic or bisyllabic, presented alone or with carrier phrases. One of the most widely used word recognition tests is the Northwestern University Auditory Test No. 6 (Tillman & Carhart, 1966), in which monosyllabic words are presented in a carrier phrase: "Say the word___." Third, a sentence test, as the name implies, uses sentences as the test stimuli and examines the ability of recognizing the words embedded in each test sentence. In a sentence test, more syllables are presented in each utterance and normally more syntactic and semantic cues are available than a word-based test. It is acknowledged that linguistic contexts in a meaningful sentence provide a certain level of predictive information and this is true in the real world. Based on these considerations, sentence tests are closely related to daily speech communication and have relatively high content validity, allowing a more realistic measure of a listener's speech recognition ability compared to nonsense syllable tests and word-based tests. For example, the Quick Speech-in-Noise (QuickSIN) Test (Killion, Niquette, Gudmundsen, Revit, & Banerjee, 2004) is a sentence test. Some of the sentence tests use materials that purposely eliminate the contextual relationship within each sentence while the grammatical structure is still maintained. By doing so, a semantically low-context sentence with syntactically correct construct is composed and the possibility of predicting the target words is minimized. A Danish sentence test, Dantale II (Wagener, Josvassen, & Ardenkjaer, 2003), serves as an example. This test consists of 160 sentences, each of which is composed of 5 key words: a name, a verb, a number, an adjective, and a noun. Ten different words are available for each of the five word positions. An example is: *Michael had five new plants*. A fourth type of material is continuous discourse, which is composed of a number of sentences and describes a given topic. Some people also consider this a sentence test. A typical example is the Connected Sentence Test (CST) (Cox, Alexander, & Gilmore, 1987) which includes 48 passages, each of which consists of 10 sentences and 25 key words. Similar to a meaningful sentence test, various forms of contextual cues exist in the CST. Sentence and continuous discourse tests are very similar to daily speech communication and thus are considered to be more ecologically valid than word-based tests.

Scoring strategy. After completing a speech recognition test, a numerical value is often assigned to quantify a listener's performance. Scoring strategies are varied and depend upon the nature of tests. A common approach is to calculate the percentage of correctly recognized syllables and words, or key words in sentences (e.g., Northwestern University Auditory Test No. 6). With this strategy, the higher the score, the better the performance. A second method is to utilize an adaptive strategy for tracking a target performance level, such as 50% correct and 80% correct (e.g., Hearing in Noise Test;

Nilsson, Soli, & Sullivan, 1994). This strategy produces a level of stimulus at which a certain performance (e.g., 50% correct) occurs. With this strategy, some sentence tests require the listener to repeat the entire sentence correctly (e.g., Hearing in Noise Test; Nilsson et al., 1994). Both scoring methods are widely used. With the former scoring method, recognition performance is evaluated under a given stimulus level. However, with the latter method, stimulus level at a given speech recognition threshold is measured.

Test format. Speech recognition tests could be classified into open- and closed-set tests. Gelfand (2001) summarized the characteristics of both formats. An open-set test strategy means the subject must respond without any prior knowledge of what the possible alternatives might be and use their knowledge of the language and linguistic content to respond. In contrast, a closed-set test strategy means the patient is provided with a choice of several response alternatives. Sentence tests and continuous discourse tests are commonly formulated as open-set. The QuickSIN and CST are two tests which fall within this category. On the other hand, the closed-set test potentially could be used for nonsense syllable tests or word-based tests. An example of a closed-set test is the Four Alternative Auditory Feature (FAAF) test (Foster & Haggard, 1987). In this test, each target word is presented with a carrier phrase: “Can you hear ____clearly?” and four words, which are very similar in pronunciation, are provided as possible answers. Taken together, both open- and closed-set strategies are widely used. Open-set strategies are the most popular method for clinical assessment. Compared to an open-set strategy, a closed-set strategy can reduce the effect of word frequency, a patient's vocabulary, and learning effect. Also, it allows a particular aspect of speech recognition to be measured (e.g., initial consonant recognition) by carefully designing the alternatives (Gelfand, 2001). In addition, effects of guessing on a closed-set test are unavoidable. The guessing factor is related to the number of response alternatives given to choose from. For example, guessing would yield the correct answer one-fourth (25%) of the time on the FAAF test.

Test condition. Speech recognition performance could be examined in quiet or in noise for addressing different aspects of hearing status and prescribing amplification. When measuring an individual's speech recognition performance in quiet, his or her speech recognition threshold as well as supra-threshold performance could be obtained. This information could be used to validate the listener's audiometric outcome, and a baseline of the impairment could be drawn. On the other hand, when measuring in noise, the corresponding speech recognition performance reflects the ability of understanding speech signals with simultaneously presenting noise. It is well known that one of the most common complaints expressed by people who are hearing-impaired is difficulty understanding speech when listening in competing noise. About 30% of hearing aid users are still not satisfied with their hearing aids in noisy situations (Kochkin, 2010). Furthermore, performance on a speech-in-noise test can be used as a basis for the selection of amplification technologies (e.g., directional microphones) and even for audiologic rehabilitation. All the above considerations stress the exceptional importance of incorporating a speech recognition test in competing noise in a clinical and/or research test battery.

When masking speech signals, masking noises are usually broadband signals varying in spectrum shape and/or envelope modulation. Amplitude modulated masking noises provide short-term moment-to-moment SNR increment when speech signals are presented during the dips of the noise envelope. Evidence has been reported that speech cues obtained from those less adverse moments are beneficial to speech recognition performance for listeners with normal hearing (e.g., Bacon, Opie, & Montoya, 1998; Dubno, Horwitz, & Ahlstrom, 2002, 2003; Eisenberg, Dirks, & Bell, 1995; Festen & Plomp, 1990; Gordon-Salant & Wightman, 1983; Gustafsson & Alinger, 1994; Liu & Kewley-Port, 2004; Souza & Turner, 1994; Summers & Molis, 2004; Takahashi & Bacon, 1992). However, listeners with hearing impairment appear to receive little or even no benefit from masker modulation in their unaided speech recognition performance (e.g., Festen & Plomp, 1990; Gordon-Salant & Wightman, 1983; Souza, Boike, Witherell, & Tremblay, 2007; Souza & Turner, 1994; Wilson, Carnell, & Cleghorn, 2007) and aided speech recognition performance (e.g., Rosengard, Payton, & Braida, 2005; Stone, Moore, Wojtczak, & Gudgin, 1997) due to the degraded temporal resolution abilities.

In summary, a variety of speech recognition tests is available for various needs. Numerous speech recognition tests have been used for assessing release time superiority and its relationship to cognitive abilities. Among those used are monosyllabic word tests (e.g., Four Alternative Auditory Feature test) and sentence tests (e.g., Hearing in Noise

Test). It is probable that differences in the amount of linguistic context in these tests have impacted, to some extent, the results of previous investigations.

Psychometric Function

Concepts of Psychometric Function

A psychometric function relates an observer's performance to an independent variable, usually some physical quantity of a stimulus in a psychophysical task (Wichmann & Hill, 2001). The psychometric function is usually S-shaped in its graphical representation, which is fitted according to a mathematical equation to a set of discrete data points obtained under a series of stimulus levels. The mathematical equation is usually a sigmoid function, such as the Weibull, logistic, cumulative Gaussion, or Gumbel distribution. With the fitted psychometric curve, behavioral performance is estimated for any stimulus level within an appropriate range. An example of a psychometric function is given in Figure 1. Speech recognition performance in percent correct is plotted as a function of SNR. The speech recognition performance increases as the SNR increases, but the increment rate varies. The stimulus level (SNR) that corresponds to a given behavioral performance level (e.g., 50% correct) and the slope of the fitted psychometric curve at the same level of behavioral performance are the two parameters in which researchers are most interested. For a given level of performance, the stimulus level serves as a measure of the required stimulus intensity, while the slope of the fitted function serves as a measure of the change in performance with changing x-axis values (Wichmann & Hill, 2001). As the example shown in Figure 1, the SNR for the 50% correct point (point A) is about -1 dB and the slope of the curve at point A is about 10% per dB.

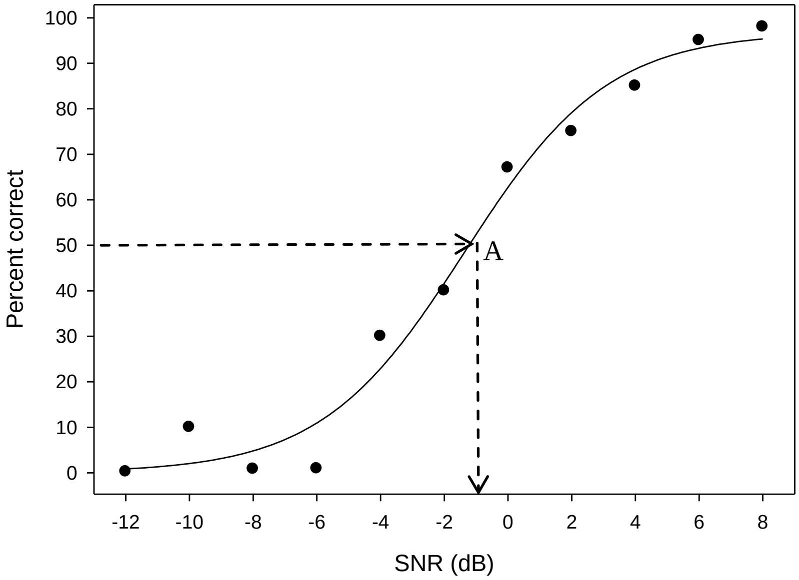

Figure 1. Example of a psychometric function showing speech recognition performance in percent correct as a function of SNR. The individual data points are fitted with a logistic psychometric function.

Application to Audiology and Hearing Research

Since psychometric functions can demonstrate the relationship between perception and psychophysical stimuli, they are also widely used in audiology and hearing research. Arlinger (1991) defined psychometric functions from an audiological perspective: A psychometric function represents the probability of a certain listener's response as a function of the magnitude of the particular sound characteristic being studied. Another term, Performance-Intensity (PI) function, is seen in many articles and books. The PI function is a type of psychometric function, which shows performance (e.g., speech recognition performance) as a function of some stimulus parameter (e.g., speech level) (Gelfand, 2001). In audiology and hearing research, this term is often used as a synonym for psychometric function. A PI function has been proven to be a powerful behavioral tool in evaluating speech recognition performance. For example, when assessing speech recognition performance in conditions with improving SNR, it is of interest to measure how well a listener understands speech as more and more speech information is released from masking. Compared to a single measure of speech recognition threshold, a PI function exhibits speech recognition performance in percent correct over a larger range of test conditions. It describes the cumulative distribution of useful speech information across the amplitude domain, as speech rises from almost inaudibility to full audibility (Boothroyd, 2008).

Psychometric functions, as an evaluation tool, have been used in numerous studies to evaluate speech recognition performance. For example, Foster and Haggard (1987) measured speech recognition performance of listeners with normal hearing under a series of conditions differing in SNR with a speech recognition test method they developed: Four Alternative Auditory Feature (FAAF) test. The psychometric function constructed with the speech recognition scores and the corresponding SNRs provided an intuitive tool in evaluating the validity of the FAAF test material. In addition, Cox and Xu (2010) and Lunner and Sundewall-Thoren (2007) used psychometric functions for comparing aided speech recognition performance in a number of SNR conditions when the hearing aid compression time constants and the masker modulation were varied. Cox and Xu (2010) further suggested that the slope of a psychometric function might be an indicative parameter in evaluating real-world release time preference.

The usefulness and potential value of psychometric functions cannot be stressed enough. Boothroyd (2008) considered psychometric functions a tool which had been neglected and underused for both hearing research and clinical audiology.

Summary

Short and long release time settings of compression hearing aids have considerable impact on the way speech signals are amplified and can dramatically alter the envelope of speech signals. With inappropriate release time settings, speech understanding performance of hearing aid wearers might be compromised followed by reduced hearing aid benefit and satisfaction. The importance of release time selection has been acknowledged and a number of studies have been undertaken to seek the overall superiority of either type of release time. Previous studies investigated the advantages and disadvantages of different release times under a variety of test conditions with both objective and subjective measurements. The findings were inconclusive and numerous factors could possibly account for the diversity.

More recent research has established a connection between release time superiority and cognitive abilities (primarily working memory capacity). Inconsistent results were obtained as well. Insights were obtained after a careful inspection of the test materials, including both speech recognition and cognitive performance. First, a variety of speech recognition tests were used in the reviewed studies and these tests differed in many ways, for example, language, scoring strategy, test format, and linguistic context. Among the potentially influential factors, linguistic context of speech test materials, which was somewhat associated with cognitive abilities of hearing aid wearers, was suspected to be a possible explanation of the diverse findings. Second, it was noticed that different types of cognitive test methods were used in the small body of literature. These methods measured different dimensions of cognition and differed in effectiveness. Therefore, the cognitive abilities measurements and the corresponding grouping of high and low cognitive performance differed substantially.

With regard to such concern, a review of cognition and working memory provided guidance in selecting appropriate cognitive tests. Akeroyd (2008) suggested that the reading span task was probably the most-effective task for examining working memory capacity. The first reading span test was described in greater detail.

In addition, an in-depth illumination of speech recognition testing was provided, focusing on test material, scoring strategy, test format, and so on. Along with a brief introduction to the strategy of information processing, the critical role of linguistic context in speech test materials was also emphasized. With different levels of linguistic context, speech recognition test materials used in the aforementioned studies about release time superiority were not homogeneous and presumably resulted in different degrees of cognitive involvement, and consequently, produced diverse recognition outcomes.

A performance-intensity function (psychometric function) is an informative tool for displaying speech recognition performance under a series of test conditions. It provides an overall view of recognition performance as a function of stimulus condition. Comparisons carried out in terms of performance-intensity functions are indicative of a trend of difference, which offers exceptional insight into the performance difference under a wide range of conditions.

Based on this review, a question was raised as to how linguistic context in speech recognition test materials influences the determination of release time superiority for hearing aid wearers with various cognitive abilities. In order to answer this question, a more comprehensive test battery for evaluating speech recognition performance is required. This test battery should incorporate speech recognition tests with both low and high linguistic contexts, in order to effectively tap into both top-down and bottom-up speech processing strategies. In addition, an effective measure of cognitive ability that targets working memory capacity is also needed. It is reasonable to expect that better control of the tests used for measuring speech recognition and cognitive performance would result in a better understanding of the relationship between cognitive ability and release time superiority.

Research Questions

The primary goal of the current study was to further extend the line of investigation to address the relationship between cognitive abilities of listeners with hearing impairment and aided speech understanding performance with varying release times. In this study, aided speech recognition performance of adult hearing aid wearers was measured with three test materials differing in the level of linguistic context. A reading span test was used for measuring cognitive performance. SNRs at a given performance level were derived using performance-intensity functions and subsequently employed for comparing aided speech recognition performance with different release time settings.

The specific research questions were:

1. What is the relationship between cognitive abilities and aided speech recognition performance in noise with short and long release times when context-rich test materials are used?

2. What is the relationship between cognitive abilities and aided speech recognition performance in noise with short and long release times when low context test materials are used?

Chapter 3

Methods

This chapter describes the research methods which were used in the present study. The goal was to assess the superiority of short or long release time processing used in digital wide dynamic range compression (WDRC) hearing aids. The present study carried forward a line of research exploring the relationship between cognitive abilities of hearing aid users and their aided speech understanding performance with varying release times. To explore the effect of linguistic context in different types of speech, aided speech recognition performance was measured with three speech recognition test materials. Specifically, each participant's cognitive ability was measured with a reading span test. Then, hearing aids with adjustable compression time constants were fitted binaurally to each participant, followed by aided speech recognition testing using speech recognition test materials differing in linguistic context. Interactions between cognitive ability and release time were assessed for each speech recognition test.

The present study was a double-blinded nonrandomized intervention study. The research method is described in detail in the following seven sections: (1) participants, (2) general procedure, (3) hearing evaluation, (4) hearing aid fitting, (5) cognitive test, (6) speech recognition tests, and (7) data analysis and statistical power.

Participants

Thirty-four adult hearing aid users participated in this study. Individuals were required to fulfill the following eligibility criteria: a) post-lingual mild to moderate sensorineural hearing loss bilaterally; b) essentially symmetrical loss, for which three-frequency (500Hz, l000Hz, and 2000Hz) average hearing loss difference between ears was no more than 15 dB; c) a type “A” tympanogram with compliance above 0.3 milliliter for each ear; d) no history of ear surgery, chronic middle or outer ear pathology, retrocochlear or fluctuating hearing loss; e) relatively good vision (with or without eyeglasses) to read words displayed on a computer monitor; f) use of English as first language; and g) adequate literacy to complete informed consent, cognitive test, and speech recognition tests. These participants were recruited from the Hearing Aid Research Laboratory subject database and the Memphis Speech and Hearing Center clinic. The participants were contacted by mail or telephone. Participants who completed the study were monetarily compensated for their participation.

General Procedure

All tests were administered in the University of Memphis Hearing Aid Research Laboratory (HARL). Two visits were required for each participant. The test battery comprised a hearing evaluation, a cognitive test, a hearing aid fitting, and three speech recognition tests.

In session one, the subject received a brief introduction to the study and then filled out the consent form. A hearing evaluation was carried out for obtaining information about the subject’s current hearing loss and unaided speech recognition abilities. Then, a reading span test was given to assess the subject’s cognitive abilities. After completing the reading span test, hearing aids were fitted bilaterally to the subject. There was no real-world acclimatization period for the purpose of maximizing effects of different release times (Rönnberg, 2003). The hearing aids were kept in the HARL.

In session two, the subject wore the hearing aids which were fitted to his or her hearing loss. The subject’s aided speech recognition performance with the first release time setting was evaluated under several SNR conditions using three speech recognition tests: the American Four Alternative Auditory Feature (AFAAF) test (Xu & Cox, 2010), the Bamford-Kowal-Bench Speech-In-Noise (BKB-SIN) test (Etymotic Research, 1985), and the Words-In-Noise (WIN) test (Wilson, 2003). After completing all speech tests with the first release time setting, the second release time setting was programmed to both hearing aids. The same speech recognition tests were administered again with different lists. In addition to an immediate scoring, each subject’s responses were digitally recorded for intra-judge scoring reliability.

Each part of the test battery is discussed in more detail in the following sections.

Hearing Evaluation

A hearing evaluation was performed on each subject for determining basic hearing ability and participation eligibility. The evaluation battery comprised otoscopy, tympanometry, ipsilateral acoustic reflex thresholds, air conduction pure tone thresholds, and suprathreshold word recognition testing. First, each subject’s ear canals and tympanic membranes were inspected visually with an otoscope bilaterally. Second, tympanometry using a 226Hz probe tone and ipsilateral acoustic reflex thresholds at 1kHz and 2kHz were measured using an Earscan immittance meter (Micro Audiometrics) for evaluating the subjects' middle ear function. Third, the subjects' air conduction thresholds were measured using a Grason-Stadler GSI-61 clinical audiometer with a pair of ER-3A insert earphones. Last, suprathreshold word recognition performance was measured to evaluate each subject's unaided speech recognition ability. A method reported in Guthrie and Mackersie (2009) was used in this study. According to this method, the sensation level is referenced to the 2kHz air conduction threshold of each ear in dB HL. That is, after the audiometer is set for testing speech audiometry, its dial level is set equal to the sum of the nominal 2kHz threshold level and the corresponding sensation level. The sensation level is selected according to the following rules:

- 2kHz threshold < 50 dB HL: sensation level = 25 dB
- 2kHz threshold = 50-55 dB HL: sensation level = 20 dB
- 2kHz threshold = 60-65 dB HL: sensation level = 15 dB
- 2kHz threshold = 70-75 dB HL: sensation level = 10 dB

For example, if a subject's right ear air conduction threshold at 2kHz is 50 dB HL, then the sensation level for assessing word recognition performance is 20 dB. As a result, the speech signals will be presented to the subject's right ear with the audiometer dial setting of 70 dB HL. Results from Guthrie and Mackersie (2009) suggest that this method avoids the need for additional testing and produces the highest word recognition scores for mild to moderate gradually sloping hearing losses, as well as steeply sloping hearing losses. In this study, two 50-word lists were used, CID W-22 list 1A and 2A recorded on the AudiTec CD (St. Louis, MO), one for each ear.

Hearing Aid Fitting

Starkey S Series 9 behind-the-ear style hearing aids were used in the present study. They were digital WDRC hearing aids with 12 compression channels ranging from 200 Hz to 6000 Hz. The reason for choosing this type of hearing aid was that the time constant setting was adjustable. In the present study, the nominal compression time constant settings (attack/release) for short and long processing were: 15/50 milliseconds and 20/2000 milliseconds, respectively. This type of hearing aid also provided some advanced features, such as directional microphones, digital noise reduction, and feedback cancellation. However, all advanced features except feedback cancellation were inactivated. In addition, as many as four memories were available for different environments and directional settings. Only one out of the four memories was used. There was no volume control wheel, program control button, or on/off switch on the hearing aid.

The hearing aids were bilaterally fitted with temporary earmolds (temporary canal tips) without a vent. For initial programming, the subject’s air conduction hearing thresholds were entered in to the Starkey hearing aid fitting software: Inspire 2010. The hearing aids were programmed to the subject’s hearing loss according to the National

Acoustics Laboratories, Non-Linear, version 1 (NAL-NL1) prescription method (Byrne, Dillon, Ching, Katsch, & Keidser, 2001). After the initial programming, real-ear measurements were carried out one ear at a time in the HARL. The Speechmap program in the Audioscan Verifit hearing aid test system was used. First, a probe tube was inserted into the subject’s ear canal with a temporary earmold. The tip of the probe tube was within approximately five millimeters from the tympanic membrane. The hearing aid that was programmed for this ear was coupled to the temporary earmold and turned on. Second, under the Speechmap program, audiometric and other pertinent information was entered. After that, hearing aid outputs for soft speech (presented at 55 dB SPL), raised level speech (presented at 70 dB SPL), and maximum power output (MPO) levels (tone bursts presented at 90 dB SPL) were measured and compared to the corresponding NAL-NL1 targets. The speech (Speech-std-1 in Speechmap) used for verifying soft speech and raised level speech targets was a passage spoken by a male talker with average vocal effort. The speech signals were shaped to the long-term average speech spectrum (LTASS) recommended by Cox and Moore (1988). Criteria of the verification measures were: (1) the median levels of amplified soft speech and raised level speech should match within 5 dB of the targets for soft speech and raised level speech, respectively; and (2) the maximum output level should never exceed the MPO targets and should be within 10 dB of them. If the targets for soft speech and raised level speech could not be met at the same time, a compromise was made to make sure the raised level speech was not too loud. In order to achieve relatively large release time difference between short and long release time processing, compression ratios were set to at least 1.2 for channels from 500Hz to 1500Hz, and at least 1.3 for channels from 2000Hz to 5000Hz. The two minimum compression ratios were determined based on a preliminary measurement (see Appendix A). It is also critical that the compression ratio for each channel was lower than 3.0 for the purpose of minimizing sound distortion. Fine adjustments were performed as needed through the Inspire 2010 software to meet the criteria.

In addition to the real-ear measurements, subjective verification was applied to optimize hearing aid fitting. Two aspects were evaluated: loudness balance and loudness tolerance. Because each subject was bilaterally fitted with hearing aids, verification of loudness balance between two ears was necessary and crucial. Loudness balance was measured by presenting an International Collegium of Rehabilitative Audiology (ICRA) noise used in Speechmap at 65 dB SPL to the subject at 0° azimuth. The subject was asked whether the sound was heard in the center of his or her head. If not, the overall gain in the louder hearing aid was reduced until the subject reported equal loudness. From then on, the same amount of gain adjustment was applied to both hearing aids if further adjustment was needed. The second subjective evaluation focused on loudness tolerance, because it was critical to provide listeners who were hearing-impaired with amplification that made loud sounds loud but not uncomfortable. Loudness tolerance was evaluated by presenting the tone bursts that were used for MPO measurements from the Audioscan Verifit to the subject at 0° azimuth. The subject was asked to indicate (by raising his or her hand) if he or she experienced sounds that were uncomfortably loud. If the indication was persistent across frequencies, MPO levels of both hearing aids were brought down until most of the sounds were not uncomfortably loud.

After completing all subjective assessments, Speechmap procedures were conducted again on the subject’s ears as well as in a 2-cc HA-2 coupler for documentation purposes. The settings for both hearing aids were saved to the hearing aid fitting program. When the subject returned for session 2, the hearing aids were programmed to the saved settings and verified in the HA-2 coupler.

Half of the participants were fitted with the short release time setting first and then with the long release time setting. The other half of the participants were fitted in the opposite order.

Cognitive Test

A computer-based reading span test was used to evaluate the subjects’ cognitive abilities. This test was developed in Sweden (Rönnberg, Arlinger, Lyxell, & Kinnefors, 1989) based on the Baddeley, Logie, Nimmo-Smith, and Brereton (1985) version of reading span test. The original version, written in Swedish, has been used in a number of studies associated with audiology and hearing science (e.g., Foo et al., 2007; Lunner, 2003; Rudner et al., 2009; Rudner, Foo, Sundewall-Thoren, et al., 2008). Later, this test was translated into English and used in England for a study which investigated hearing impaired listeners’ benefit from amplification (Davis, 2003). In the present study, the English version of this reading span test was implemented. The subjects were asked to read each sentence out loud and judge whether the sentence made sense. Then, they were asked to recall either the first or the final words of a presented sequence of sentences in correct serial order.

This reading span test comprised 54 test sentences and three practice sentences. The test sentences were presented in groups that range in size from three to six sentences per group. There were three groups of sentences for each of the four sizes. Each sentence was composed of three categories: a person, a verb, and an object. Among all test sentences, half of the sentences were nonsense sentences (e.g., “The train sang a song”) and the other half were normal sentences (e.g., “The girl brushed her teeth”). The software displayed the sentences on a computer monitor in a word-by-word fashion, at a rate of one word per 0.8 second. The subjects were instructed to respond “yes” to the sentences which were normal and respond “no” to sentences which were nonsense during a 1.75-second interval after each sentence. At the completion of each group of sentences, the tester said either “First” or “Last,” indicating that the subject should start to recall either the first or the final words of each previously presented sentence in their correct serial order. The order of recalling the first or final words was randomized. The three practice sentences served as a practice group before actual tests. In the testing phase, the test sentences were presented in groups in ascending order until the last group with six sentences was completed. The percentage of the words that was correctly recalled was the performance measure. All responses from the subject were recorded on a reading span score sheet by the tester.

Speech Recognition Tests

Three speech recognition tests, which differ in the amount of linguistic context, were used. They were the American Four Alternative Auditory Feature (AFAAF) test, the Bamford-Kowal-Bench Speech-in-Noise (BKB-SIN) test, and the Words-in-Noise (WIN) test. Among these tests, the WIN is an open-set word-based test and the effects of working memory and inter-word context on recognition performance are minimized (Wilson, McArdle, & Smith, 2007). This test provides minimal linguistic context, so no prediction is possible. Listeners must rely on bottom-up processing for understanding the test words. The WIN is considered a context-low material. The BKB-SIN is an open-set sentence test and the contextual cues within each test sentence are substantial. Therefore, the BKB-SIN is considered a context-rich material involving considerable top-down processing. The AFAAF is a closed-set word-based test. Because the displayed alternatives for giving responses to a test word might provide some predictive clues (e.g., phonological cues), the AFAAF is considered intermediate between the WIN and the BKB-SIN with regard to the amount of non-acoustic cues. Additional reasons for including the AFAAF into the speech test protocol were: First, the AFAAF is a closed-set test. This test format is different from the WIN and the BKB-SIN. Second, the FAAF (a British dialect version of the AFAAF) was used in Gatehouse et al. (2003). Results of that study were different from some other studies (Cox & Xu, 2010; Foo et al., 2007) in which different speech test materials were used. Even though speech material was only one of the possible factors that accounts for the discrepancy, it was still interesting to see whether findings similar to that reported in Gatehouse et al. (2003) can be obtained when an equivalent speech test material, the AFAAF, was used.

Instrumentation and Calibration

The subjects were seated in a double-walled sound room and tested in a calibrated sound field. The acoustic environment in this sound room met the requirements that were specified in ANSI S3.1-1999 (r2003). A tester administered all the tests from outside the sound room. Test stimuli of the WIN and the BKB-SIN were recorded on CDs and played on the DVD drive of a personal computer. Windows Media Player was used for playing the audio files of these two tests. The AFAAF was a software-based test which was installed on the personal computer. Audio signals from the computer soundcard were routed through the GSI-61 audiometer. Output signals from the audiometer were amplified by an ASHLY PE-800 external amplifier and then delivered to a Boston Acoustics CR57 loudspeaker in the sound room.

The Boston Acoustics CR57 loudspeaker was mounted on the wall and the center of its frontal surface was 46 inches from the floor. The sound field was calibrated using a 1/2 inch Larson-Davis pressure microphone at a grazing incidence to the loudspeaker. The location of the microphone was one meter from the frontal surface of the loudspeaker and 46 inches from the floor on axis. A Larson-Davis 800B sound level meter was connected to the microphone for measuring sound pressure levels in the sound field. Because the microphone was placed at the location of the center of the listener's head with the listener absent, sound pressure levels measured at this place were approximately identical to the sound pressure levels at the listener’s ears. The calibration procedure was performed before each session two.

Presentation levels of all test stimuli in the three speech test materials were calibrated using a dB SPL root-mean-square (RMS) measure. Details about each speech recognition test are elaborated in the following sections.

WIN

The WIN test measures the ability of listeners to understand speech in a multi-talker babble noise (Wilson, 2003). The WIN that was used in the current study had been modified based on the WIN material from the Speech recognition and identification materials, Disc 4.0. CD (Department of Veterans Affairs, 2006). The modification combined the two word-lists into one for each randomization. Thus, instead of having two lists of 35 target words each for each of the four randomizations, the modified WIN has four randomizations each of which has 70 target words. Henceforth “WIN” will refer to the modified version.

As the name implies, the WIN is a word-based test. It uses 70 monosyllabic words from the NU6 test (Tillman & Carhart, 1966). Each target word is presented with a carrier phrase: “Say the word ____.” The speech materials in each randomization are recorded on one track with two channels: one has both the speech and a multi-talker babble masker and the other has only speech for monitoring the target words. The speech signals in both channels are time-locked. The level of the speech signals in the speech-only channel does not change, whereas, in the speech-plus-masker channel, the speech level decreases with a constant masker level to form seven SNR conditions from +24 dB to 0 dB in 4 dB steps. For each SNR condition, there are 10 target words and the performance measure is the percentage of words that are correctly recognized (Wilson, 2003).

For each release time setting, aided speech recognition was measured using two randomizations. Therefore, the score for each SNR condition was calculated based on the responses for 20 target words. The test was administered with a fixed multi-talker babble noise level at 50 dB SPL and seven speech levels at 50, 54, 58, 62, 66, 70, and 74 dB SPL (Table 2). A 35-word WIN list with a different randomization was used for practice.

BKB-SIN

The BKB-SIN (Etymotic Research, 2005) is a sentence test which is composed of context-rich sentences presented with a four-talker babble masker. The sentences are spoken by a male talker and a verbal “Ready” cue is used prior to each sentence. The BKB-SIN contains 18 list pairs. List pairs one to eight each contain 10 sentences in each list while list pairs 9 to 18 each have eight sentences. In this study, only list pairs one to eight in the BKB-SIN CD one were used. Each sentence has three to four key words. Thus, there are 31 key words per list. An example of a sentence is: “The <u>cat</u> is <u>sitting</u> <u>on</u> the <u>bed</u>.” The underlined words are the key words in this sentence. The target talker and background babble of each of the eight pairs are recorded on the same channel at 10 pre-recorded SNRs from +21 dB to –6 dB with a step size of 3 dB for each sentence. Test subjects were instructed to listen to each sentence and repeat the sentence as best they could. The scoring was based on the percentage of key words that were correctly recognized at each SNR.

For each subject, the eight pairs of lists were randomly divided into two groups with four pairs each. That is, for each release time setting, four pairs of sentence lists were used. Thus, there were 248 key words (4 list pairs * 2 lists per pair * 31 words per list) in total and about 24 words per SNR. The presentation level of the speech ranged from 59 to 65 dB SPL while the presentation level of the masker ranged from 44 to 65 dB SPL (Table 2). A practice list of eight sentences extracted from list 9A was given prior to the test to familiarize the subject with the task.

AFAAF

This test was produced based on the Four Alternative Auditory Feature test (FAAF) which was originally developed in the MRC-Institute of Hearing Research, UK (Foster & Haggard, 1987). The FAAF has been widely used in the UK for hearing research (e.g., Davies, John, & Jones, 1990; Davis, Lovell, Smith, & Ferguson, 1998; Gatehouse, 1992, 1993; Gatehouse et al., 2003; Milchard & Cullington, 2004; Munro & Lutman, 2005; Shields & Campbell, 2001) and has been found to be very sensitive in evaluating speech recognition performance in various test conditions. In order to use this material in the United States, all speech materials in FAAF were regenerated in American English and the resulting test was dubbed the American Four Alternative Auditory Feature test (AFAAF). A validation study indicates that the AFAAF is essentially equivalent to the FAAF (Xu & Cox, 2010).

The AFAAF is a word-based closed-set test. It comprises 80 test words and five practice words. In each utterance, a monosyllabic key word is embedded in a carrier sentence: “Can you hear ____ clearly?” The test words vary in temporal and spectral characteristics of the initial consonants or the final consonants. The test condition can be quiet or in the presence of noise. The AFAAF runs from a computer program. The test subject listens to the presentation and selects the word he or she hears from four displayed alternatives which are very similar in pronunciation. For example, the test utterance is: *“Can you hear OLD clearly?”* and the four alternatives displayed on a computer monitor are: *HOLD*, *OLD*, *COLD*, and *GOLD*. Based on this test, the ability to discriminate either initial consonants or final consonants of the target words is evaluated. The performance measure is the percentage of the key words that are correctly identified.

For this study, the 80 test words were divided into four lists of 20 words each. The four lists were equivalent with regard to consonant place (initial versus final) and difficulties in consonant recognition. Each list had four randomizations. The five practice words were provided at the very beginning of the test to familiarize the subject with the task. In this study, an amplitude modulated noise was used as the masker. This noise (ICRA CD, track 7; Dreschler, Verschuure, Ludvigsen, & Westermann, 2001) was a talker-matched speech spectrum noise modulated by the envelope of a six-talker babble. Subjects were tested under eight SNR conditions from –9 to 12 dB SNR in 3 dB steps. The level for speech ranged from 56 to 65 dB SPL, while the level for masking noise ranged from 53 to 65 dB SPL (Table 2). For each release time setting, two randomizations were given. That is to say, eight lists were used and one list per SNR. The selection of randomizations was counterbalanced and the order of the corresponding eight lists was randomized to minimize any potential systematic effects. The AFAAF software produced percent correct scores for each list.

In summary, three speech tests, the WIN test, the BKB-SIN test, and the AFAAF test, were used in this study. For the WIN test, seven SNR conditions, from 0 to +24 dB, were examined. The speech level ranged from 50 to 74 dB SPL, while the masking noise level was fixed to 50 dB SPL. There were 20 target words for the score at each SNR. For the BKB-SIN test, speech recognition performance in 10 SNR conditions, from -6 to +21 dB, was examined. In this test, the level for speech ranged from 59 to 65 dB SPL, while the level for masking noise ranged from 44 to 65 dB SPL. There were 24 key words per SNR. For the AFAAF test, eight SNR conditions, from -9 to +12 dB, were examined. In this test, the speech level ranged from 56 to 65 dB SPL, while the masking noise level ranged from 53 to 65 dB SPL. There were 20 test words for each SNR condition. The presentation order of the three speech materials was counterbalanced across subjects to control for potential order effects owing to practice listening in competing noise.

Table 2

Presentation Levels of Speech and Noise Signals, as well as the Corresponding SNRs in the Three Speech Recognition Tests. All Speech and Noise Levels Were Measured in dB SPL (RMS) and Calibrated in the Sound Field.

	WIN						
Speech	74	70	66	62	58	54	50
Noise	50	50	50	50	50	50	50
SNR	+24	+20	+16	+12	+8	+4	0

	BKB-SIN									
Speech	65	65	65	65	65	65	65	65	62	59
Noise	44	47	50	53	56	59	62	65	65	65
SNR	+21	+18	+15	+12	+9	+6	+3	0	-3	-6

	AFAAF							
Speech	65	65	65	65	65	62	59	56
Noise	53	56	59	62	65	65	65	65
SNR	+12	+9	+6	+3	0	-3	-6	-9

Data Analysis and Statistical Power

Data Analysis

For each participant, TableCurve 2D version4 (AISN Software, Inc.) software was used to fit a psychometric function for each of the three speech tests with each of the two release time settings. The psychometric functions were best-fit, three-parameter sigmoid functions (see Equation 1) according to the empirical discrete data points.

$$y = \frac{a}{1 + e^{-\frac{x-b}{c}}} \qquad \text{(Equation 1)}$$

In this equation, *x* was SNR; *y* was the speech recognition performance in percent correct as a function of SNR; *a*, *b*, and c were parameters of a sigmoid function. The four parameters were varied for different discrete data.

The SNR values at the 50% correct point on the subject's psychometric function (SNR50) were used to quantify each participant's speech recognition performance for further statistical analyses. Thus, there was one set of data for each of the three speech recognition tests and thus there were three sets in total (Table 3). In addition, high and low cognitive performance groups were created according to the participants reading span scores. Therefore, the cognitive ability served as a between-subject factor.

A mixed model analysis of variance (ANOVA) was employed for examining the interaction between cognitive ability and release time for the three speech recognition tests. The cognitive ability served as the categorical factor, while release time served as the within-subject repeated measure factor.

In addition, benefit of short over long release time processing (Benefit-ShortRT) for each speech recognition test was calculated for each subject. Specifically, benefit scores in dB SNR were computed by subtracting SNR50 values for short release time processing from SNR50 for long release time processing. According to the mathematical procedure, a positive benefit score indicated advantage of short over long release time processing, while a negative benefit score indicated the advantage of long over short release time processing. A Pearson product-moment correlation analysis was performed to evaluate the correlation between the reading span scores and the Benefit-ShortRT scores for each speech recognition test.

All statistical data analyses were performed using Statistical Package for the Social Sciences (SPSS) Version 16 software. The significance level was set to 0.05 for ANOVAs and correlations. However, placing too great an emphasis on statistical significance level may miss important patterns that just fall above the threshold set for tests of significance. Therefore, a relatively liberal approach was used in the present study, where effects with p values close to the defined significant level were also examined.

Statistical Power

This study focused on the interaction between release time (a within-subject factor) and cognitive ability (a between-subject factor) when using each speech recognition test. All experiments were powered to detect a medium effect (effect size f = 0.25, see Cohen, 1988) of release time on speech recognition scores for the interaction of interest. For a significant level of 0.05 at 80% power, the minimal required number of participants calculated using G*power 3 program (Faul, Erdfelder, Lang, & Buchner, 2007) was 34. Therefore, a minimum of 34 participants were recruited.

Table 3

Data Obtained from the Three Speech Recognition Tests for Statistical Analyses

WIN	BKB-SIN	AFAAF
Short RT – SNR50	Short RT – SNR50	Short RT – SNR50
Long RT – SNR50	Long RT – SNR50	Long RT – SNR50

Chapter 4

Results

The purpose of the present research was to explore the relationship between cognitive abilities and aided speech recognition performance with short and long release times when speech recognition tests with different amount of linguistic context were used.

Each subject received a hearing evaluation and was bilaterally fit with hearing aids. The participants' aided speech recognition performance with the short and the long release times was measured using three speech recognition tests: the AFAAF, the BKB-SIN, and the WIN. The SNR50 obtained from the corresponding fitted psychometric functions was used to quantify aided speech recognition performance. The participants' cognitive abilities were evaluated using a reading span test. For some analyses, the reading span scores were used to separate the participants into low and high cognitive performance groups. Relationships between hearing aid users' cognitive abilities and their aided speech recognition performance with short and long release times were assessed for each of the three speech recognition tests.

The results from the present study are elaborated in the following eight sections: (1) participant characteristics, (2) hearing aid fitting, (3) cognitive test, (4) speech recognition performance, (5) correlation between cognitive abilities and benefit of short release time, (6) creating two cognitive performance groups, (7) speech recognition performance with different test materials and different release times in each cognitive group, and (8) analysis of variance for exploring relationship between cognitive abilities, release time, and linguistic context.

Participant Characteristics

Among the 34 subjects, there were 20 males and 14 females, ranging in age from 54 to 91 years (*M* = 73.6, *SD* = 9.3). Mean hearing thresholds for the 34 subjects are shown in Figure 2. These participants were all experienced hearing aid users. Their hearing aid experience ranged from 1 year to 30 years (*M* = 9.12, *SD* = 7.53). Two of the participants were unilateral hearing aid users.

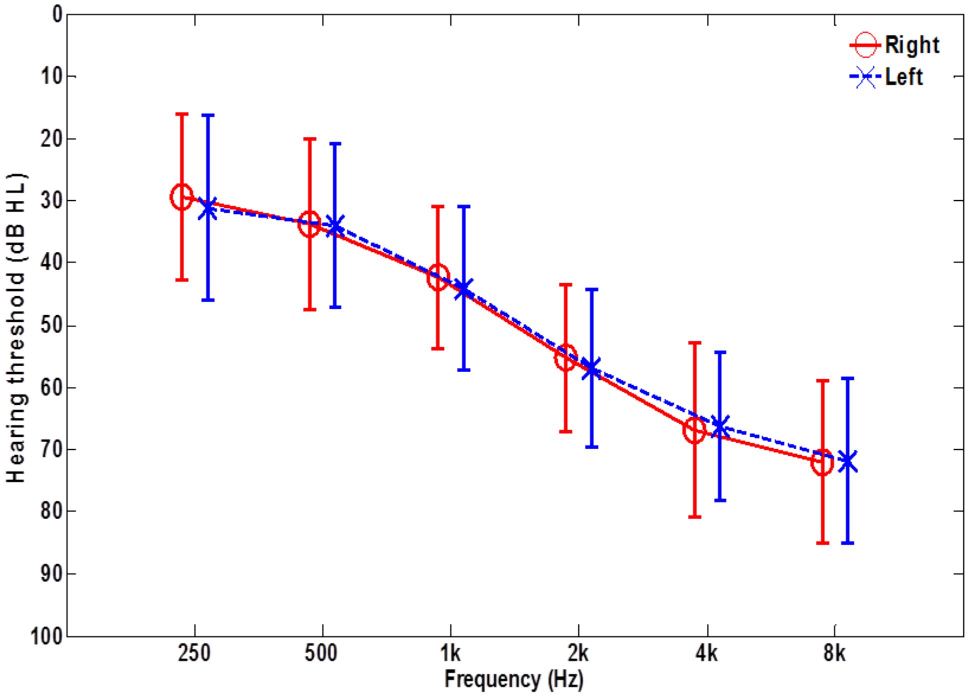

Figure 2. Mean audiogram for the 34 subjects. Error bars show ± 1 SD.

Hearing Aid Fitting

The hearing aids used in the present study were bilaterally fitted to each participant using the NAL-NL1 prescription method. Each fitting was verified with real-ear measurements and subjective verification procedures. Mean hearing aid fitting data for the 34 participants are shown in Figure 3. In this figure, open symbols represent fitting targets for 70 dB SPL and 55 dB SPL input sounds, while filled symbols represent real-ear aided response (REAR) values for the two input levels. It can be seen that the REAR values for 70 dB SPL input were within 2 dB of the corresponding fitting targets. However, the REAR values for 55 dB SPL input were approximately 2 to 5 dB lower than the fitting targets for 55 dB SPL input sounds which ranged from 500 Hz to 4000 Hz. This is probably due to the fact that the compression ratio was constrained to less than 3.0 by the researcher to minimize distortion (see Methods chapter). As a consequence, in order to match the targets for 70 dB SPL input and also ensure that the output sounds at this level were not too loud, the output levels for 55 dB SPL input sounds were slightly lower than the corresponding targets.

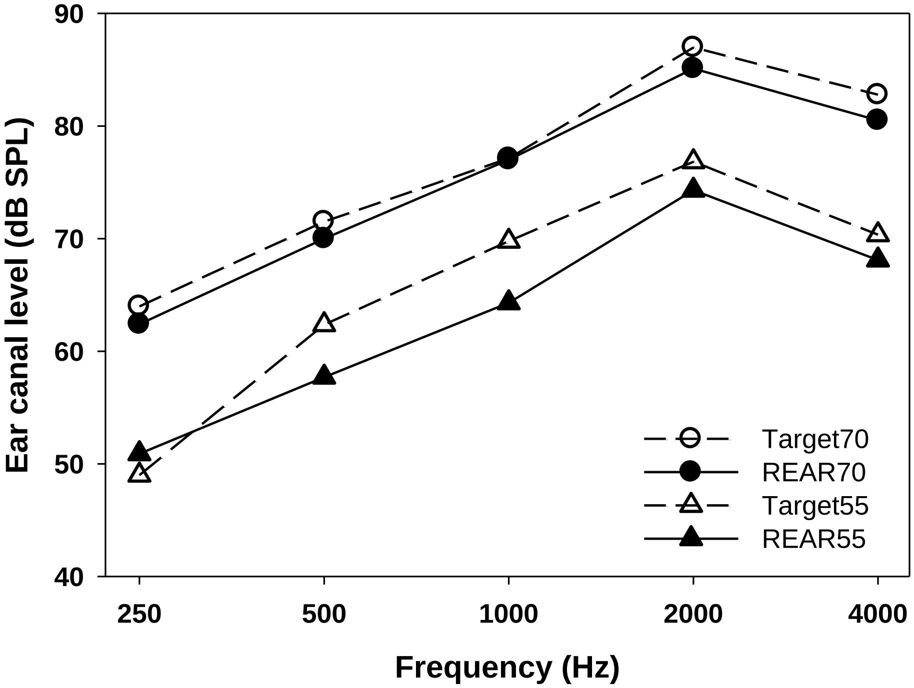

Figure 3. Mean REAR values for 55 dB SPL and 70 dB SPL speech compared to the NAL-NL1 targets across the 34 subjects (68 ears).

Given that the nominal compression time constant settings specified by the manufacturer for the short and the long release time processing were known, it was worth measuring the actual time constants for each fitting to ensure that these two time constant settings did provide a considerable release time difference. For this purpose, time constants were measured using a Fonix 7000 hearing aid test system (Frye Electronics Inc. Tigard, OR) after each fitting. Mean release time was calculated for hearing aids across frequencies from 500 to 5000 Hz. For the short release time condition, the average measured release time was 126 msec, contrasting to the corresponding nominal value of 50 msec. For the long release time condition, the average measured release time was 938 msec, contrasting to the corresponding nominal value of 2000 msec. It is important to note that the nominal time constants are determined by an engineering method using electrical circuit parameters. Even though the short and long release times measured in the test box were not equivalent to the nominal values specified by the manufacturer, there was still a substantial difference between the short and long release times.

Cognitive Test

The obtained reading span scores ranged from 9 to 56. The average score across the 34 participants was 34.2 (*SD* = 11.8). Scores for all of the participants were ranked from low to high and plotted in Figure 4. A Pearson product-moment correlation analysis was performed to evaluate the correlation between reading span score and age. The result showed that the participants' reading span scores were inversely correlated to their ages ($r = -0.453$, $p = 0.007$). A scatter plot depicts this relationship (Figure 5). This moderate correlation is consistent with previous research showing that as the age of hearing aid users increases, their cognitive performance decreases (e.g., Meguro, Fujii, Yamadori, et al., 2000).

The reading span scores collected from this study were compared to the scores collected from young listeners with normal hearing (unpublished data). The data for normal hearers were collected from 5 young listeners (1 male and 4 females), ranging in age from 22 to 31. The mean reading span scores for the five young listeners was 51 (*SD* = 5.6), which was higher than the mean reading span score from the 34 older adults with mild-to-moderate hearing impairment. Therefore, as expected, older adults with hearing impairment had lower cognitive abilities than young adults with normal hearing.

In a previous study, Davis (2003) administered the same reading span test on 332 adults with hearing impairment. In Davis's study, the participants' age range was 55 to 74. The mean reading span score was 31 (*SD* = 5) and the maximum score was 57. In the present study, the participants had similar hearing impairment. However, the mean age of the participants in the present study was higher than that of Davis (2003). Nevertheless, the mean reading span score in the present study was similar to the mean score reported in Davis' (2003) study.

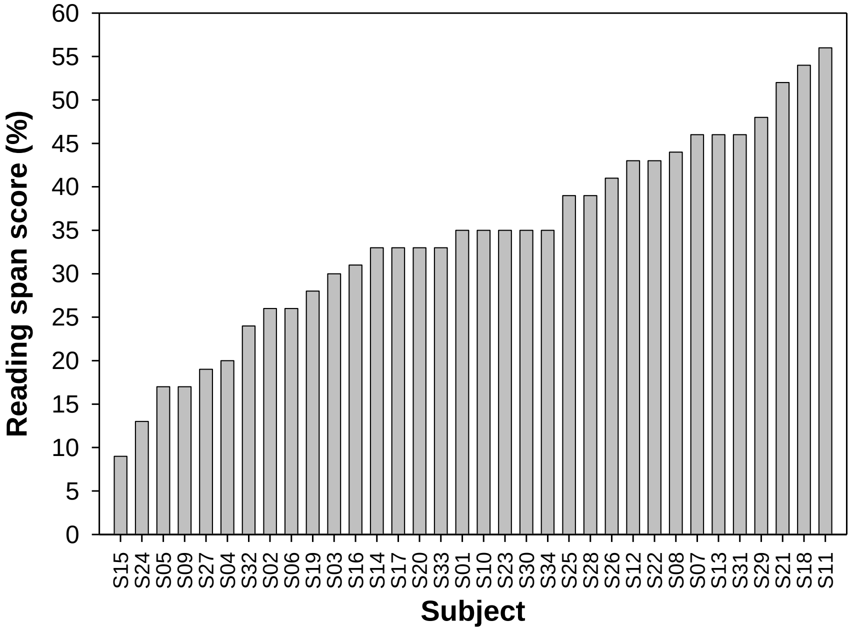

Figure 4. Reading span scores for all 34 subjects. Subjects are labeled from S01 to S34.

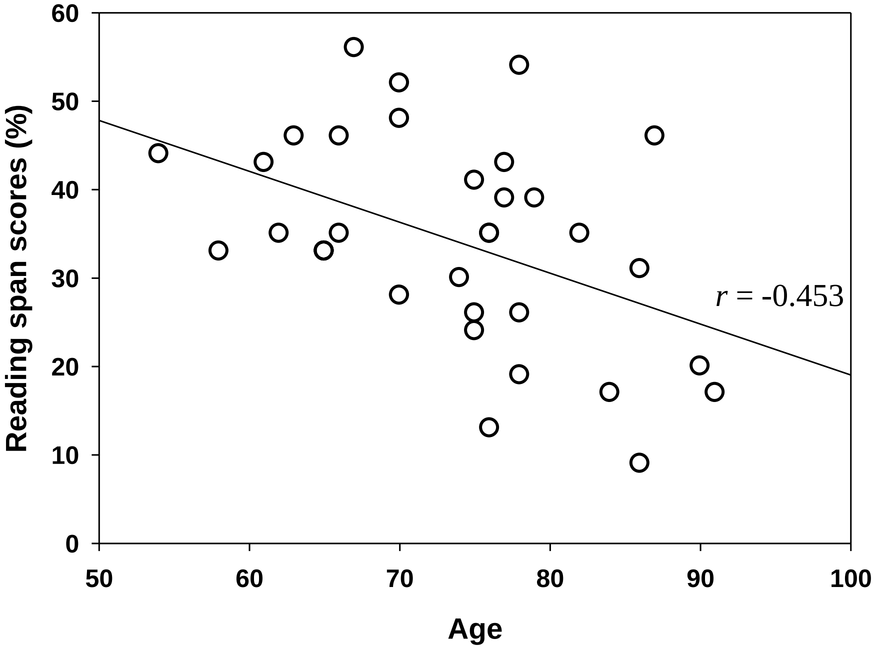

Figure 5. Scatter plot showing the correlation between the participants' reading span scores and their age. The straight line is the regression line.

Speech Recognition Performance

A psychometric function was fitted according to the discrete percentage correct scores at different SNRs for each release time for each participant. The potential fitting range was from 0% to 100% for the BKB-SIN and the WIN. For the AFAAF, however, the potential fitting range was from 25% to 100%. The reason is that the AFAAF is a four-alternative closed-set test and the chance performance is 25%. It is noted that for each test some of the participants could not achieve 100% correct in any tested SNR condition. Thus, the curve fitting method did not force the fitting to reach 100% correct at and above the most favorable SNR condition.

Lunner and Sunderwall-Thorten (2007) reported that the SNR at the 80% correct level (SNR80) of speech recognition performance showed the largest difference between low and high cognitive abilities regardless of release time and masking noise. Two other studies also used the 80% level performance to quantify speech recognition performance (Foo et al., 2007; Rudner et al., 2009). However, in the present study, after reviewing the psychometric functions for each participant and each speech recognition test, it was noticed that there were some hearing aid users whose highest speech recognition scores were lower than 80% although amplification was appropriately prescribed. Therefore, the SNR80 was not a proper performance measure for the present study. Only SNR50 values were collected.

The SNR50 values were obtained from the psychometric functions fitted for each speech recognition test with each type of release time setting. These values were used to quantify aided speech recognition performance. Mean SNR50 values and the corresponding standard deviations for the three speech recognition tests are listed in Table 4. Note that a lower SNR50 means better speech recognition performance.

Table 4

Mean SNR50 Scores and SDs for the Three Speech Recognition Tests (N = 34)

		SNR50 (dB)	
Speech recognition test	Release time	Mean	*SD*
AFAAF	Short	-6.92	3.15
	Long	-6.81	2.37
BKBSIN	Short	1.60	2.22
	Long	1.62	2.01
WIN	Short	11.19	3.33
	Long	11.33	3.98

Correlation between Cognitive Abilities and Benefit of Short Release Time

As described in earlier chapters, the FAAF was used in Gatehouse et al. (2006b) for measuring aided speech recognition performance with short and long release time processing. A visual letter monitoring test was used to evaluate hearing aid users' cognitive performance. A positive correlation of 0.30 was obtained between visual letter monitoring score and benefit for the short over the long release time processing, indicating that as the cognitive abilities of hearing aid users increase, their benefit of using short over long release time increases. In the present study, a correlation analysis between reading span score and benefit of short release time (Benefit-ShortRT) was performed to allow a parallel comparison with Gatehouse's finding.

In order to directly compare the present study with previous research, the Benefit-ShortRT scores were computed using the same strategy as three previous studies (Cox & Xu, 2010; Gatehouse et al., 2006b; Lunner & Sunderwall-Thoren, 2007). That is, the Benefit-ShortRT score was computed for each subject by subtracting the SNR50 value for the short release time from the SNR50 value for the long release time in each speech recognition test. Thus, a positive value of Benefit-ShortRT indicated that performance was better with short release time, while a negative value indicated performance was better with long release time. A data cleaning procedure on the Benefit-ShortRT scores revealed that the highest benefit values for the AFAAF and the BKB-SIN were true outliers, which violated the assumptions of Pearson product-moment correlation. One way of minimizing the impact of outliers is to change the value(s) of the variable(s) for the outlying case(s) so that they are deviant, but not as deviant as they were (Tabachnick & Fidell, 2001). In the present study, the extreme value in each of the two speech recognition tests was changed to a value that was one unit greater than the next most extreme value in the distribution. A Pearson product-moment correlation between Benefit-ShortRT scores and the reading span scores was computed for each speech recognition test. Scatter plots depicting the aforementioned correlations are shown in Figure 6.

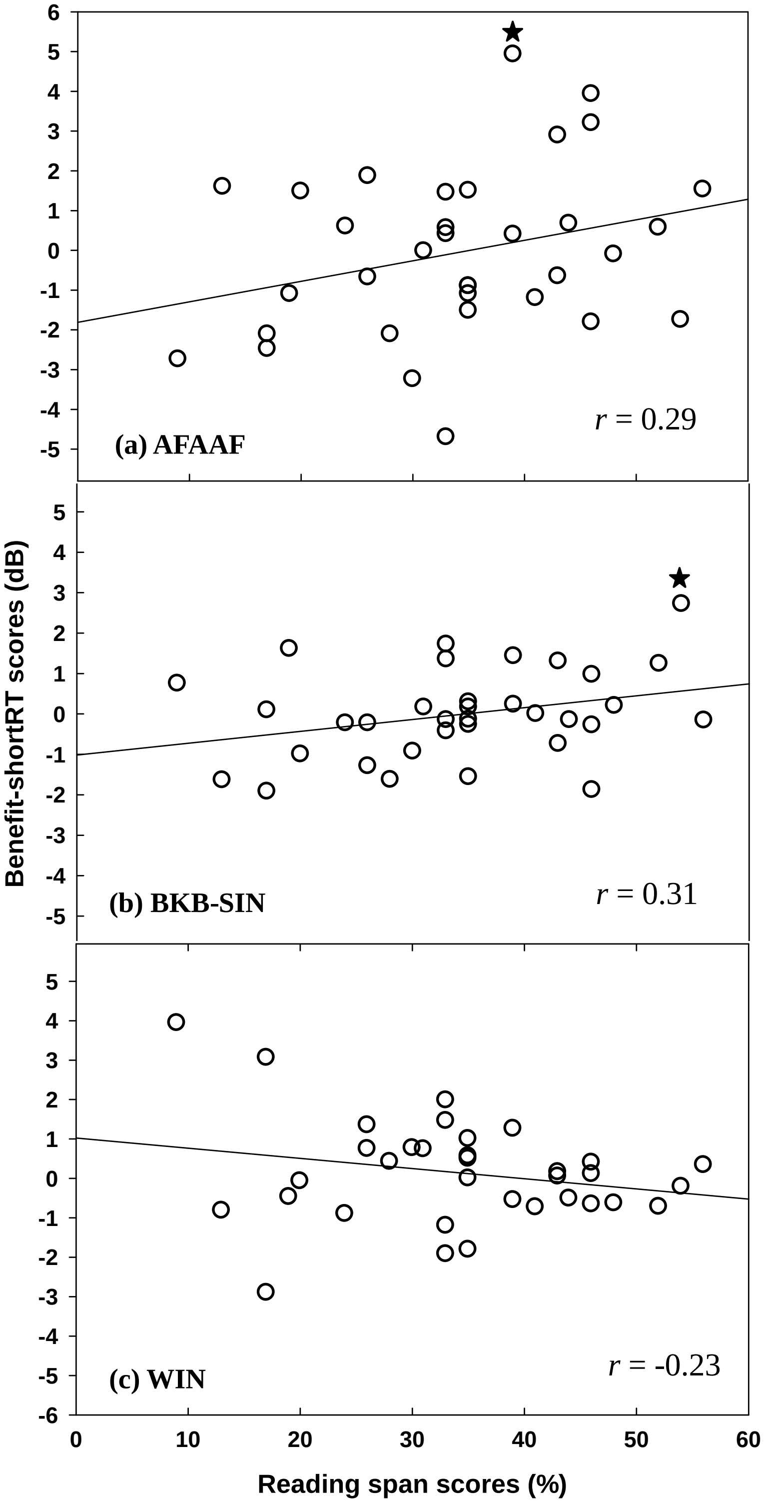

Figure 6. Scatter plots showing the relationship between the reading span scores and Benefit-ShortRT scores for the three speech recognition tests: (a) AFAAF; (b) BKB-SIN; (c) WIN. The solid line in each of the sub-plots is the regression line. The star symbols indicate the data points that were adjusted.

As seen in Figure 6, the Benefit-ShortRT scores obtained from the AFAAF and the BKB-SIN were positively related to the reading span scores, suggesting that the higher the hearing aid user's cognitive abilities, the more benefit in speech recognition the hearing aid user received from short release time processing. The correlation coefficients for the AFAAF and the BKB-SIN revealed a moderate correlation with the reading span scores ($r_{AFAAF} = 0.29$, $p = 0.097$; $r_{BKB\text{-}SIN} = 0.31$, $p = 0.076$). These correlation coefficients with the AFAAF and the BKB-SIN in the present study were similar to those in the study conducted by Gatehouse and colleagues using the FAAF ($r_{FAAF} = 0.30$, $p < 0.05$). These results supported the findings reported in Gatehouse's study and also bolstered the validity of the present study.

By contrast, the Benefit-ShortRT scores obtained from the WIN were negatively correlated with the reading span scores ($r_{WIN} = -0.23$, $p = 0.194$). The results of the WIN suggested an opposite pattern in comparison to the other two speech recognitions tests, in which that the higher the hearing aid user's cognitive abilities, the more benefit in speech recognition the hearing aid user receives from long release time processing. This is not consistent with report from Gatehouse.

Creating Two Cognitive Performance Groups

In order to create two distinct cognitive performance groups, the five subjects (S01, S10, S23, S30, and S34) from the middle of the reading span score distribution (see Figure 7) with their scores of 35 were excluded from the analyses, resulting in 16 participants in the cognitively low performance group and 13 participants in the cognitively high performance group. The age range for the participants in the cognitively low performance group was 58 to 91 years (*M* = 76.0, *SD* = 9.7), while the age range for the participants in the cognitively high performance group was 54 to 87 years (*M* = 71.1, *SD* = 8.9). The age difference between the two groups was not statistically significant ($t(27) = 1.406$, $p = 0.171$). The mean audiograms for the two groups are depicted in Figure 8. It is seen that the participants in the cognitively low performance group have 5 to 10 dB more hearing impairment on average than the participants in the cognitively high performance group across frequencies. Statistical analyses revealed that hearing thresholds between the two groups were not statistically different ($F(1, 27) = 3.595$, $p = 0.069$).

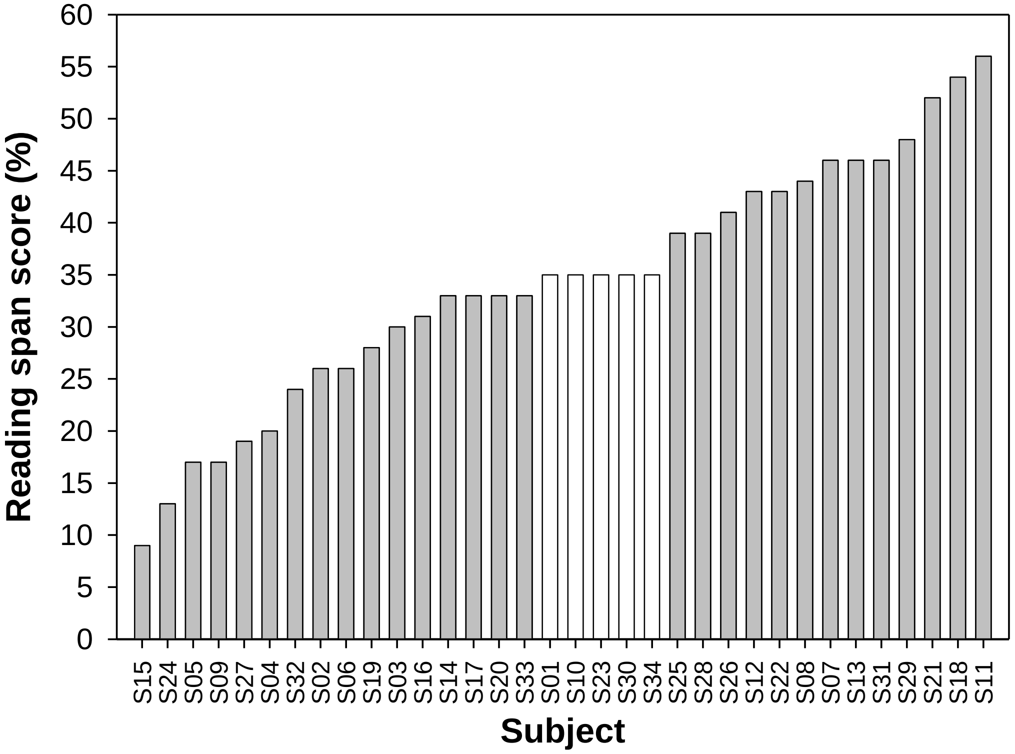

Figure 7. Subject grouping for analyses of low and high cognitive performance groups. The five subjects with their reading span scores of 35 were excluded (white bars). Among the remaining 29 subjects (gray bars), those whose reading span scores were lower than 35 were considered cognitively low performance subjects (16 subjects) and those whose reading span scores were higher than 35 were considered cognitively high performance subjects (13 subjects).

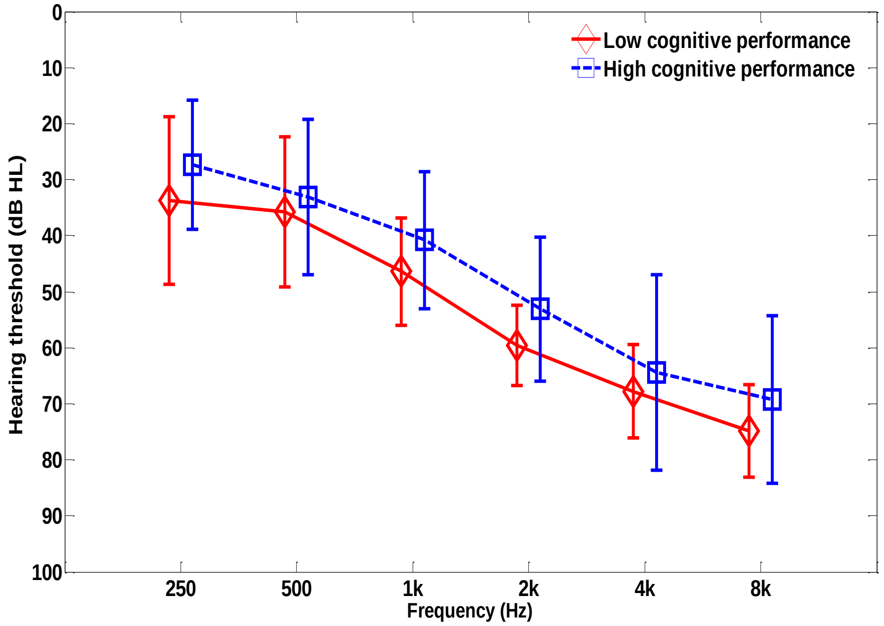

Figure 8. Mean audiograms for the low and the high cognitive performance groups. In each group, hearing thresholds for the left and the right ears were combined.

Speech Recognition Performance with Different Test Materials and Different Release Times in Each Cognitive Group

After separating the participants into two cognitive groups, aided speech recognition performance with short and long release times was compared for each group for each of the three speech recognition tests (AFAAF, BKB-SIN, and WIN). For this purpose, mean psychometric functions were computed. Psychometric functions for each cognitive group and each speech recognition test with both release times are shown in Appendix B. In addition, individual aided speech recognition scores with short versus long release time are plotted in Figure 9 (a-c) for each of the three speech recognition tests. In this figure, speech recognition scores with the long release time are plotted as abscissa, while scores with the short release time are plotted as ordinate. Data points located on the main diagonal line indicate no difference between the long and the short release times. Data points located below the main diagonal line indicate better performance with the short release time. Data points located above the main diagonal line indicate better performance with the long release time. A summary of the data point distribution for the three speech recognition tests is given in Table 5. In this table, percentage of participants who had better speech recognition performance with the short release time is reported.

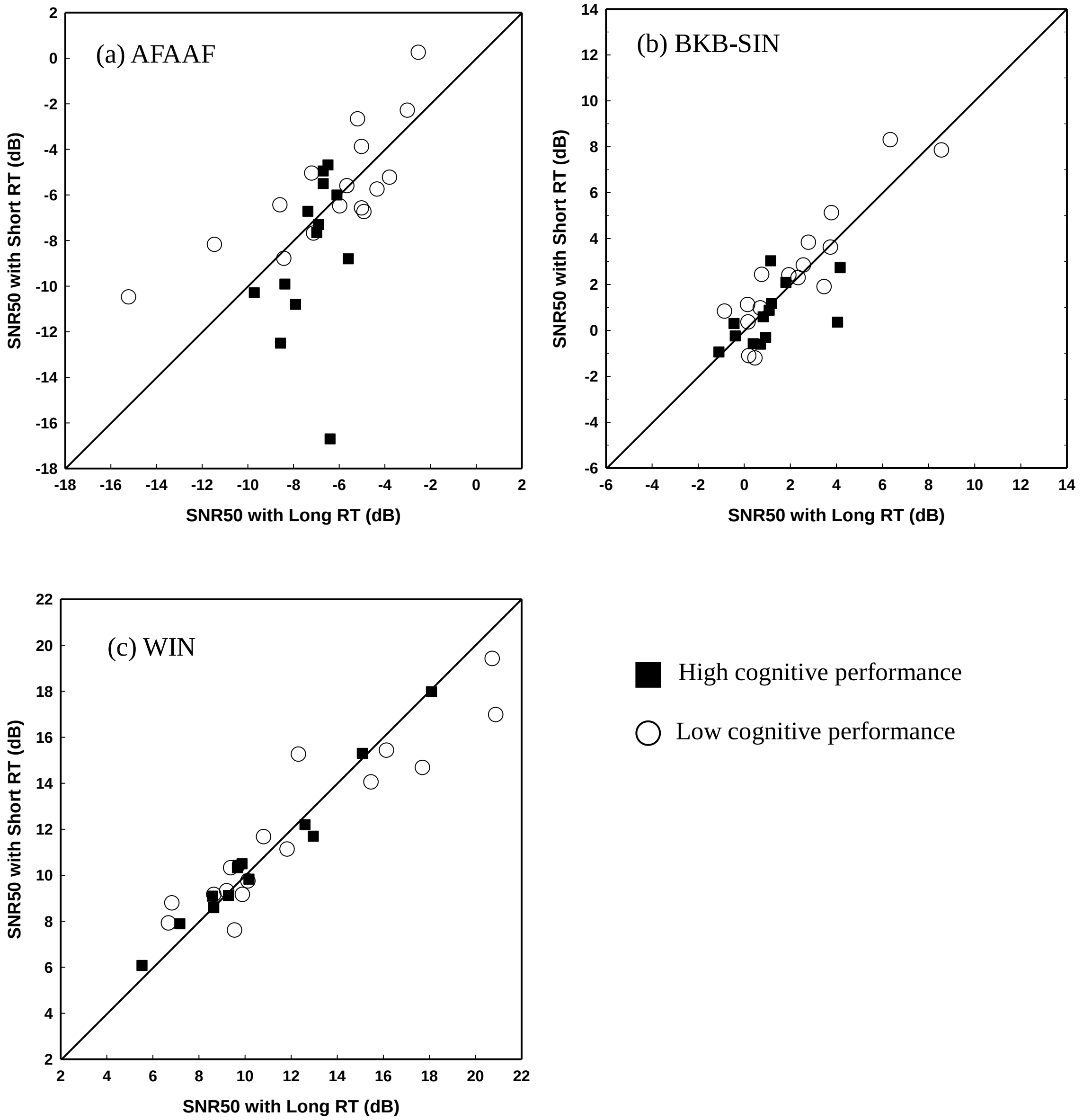

Figure 9. SNR50 scores with short and long release times when using (a) the AFAAF, (b) the BKB-SIN, and (c) the WIN. The abscissa and the ordinate in each plot show a 20 dB range.

Table 5

Percentage of Participants Who Had Better Speech Recognition Performance with the Short Release Time

	Better speech recognition performance with short release time (%)		
	AFAAF	BKB-SIN	WIN
High cog. group	62	54	38
Low cog. group	44	38	56

Analysis of Variance

In order to provide statistical assessment of the relationship between cognitive abilities, release time, and linguistic context, a mixed model repeated measures ANOVA was performed. SNR50 scores obtained with the three speech recognition tests were used in this analysis. To differentiate from other repeated measures ANOVAs in which only a portion of the full dataset was used, this mixed model repeated measures ANOVA is described in this document as the full model ANOVA. There were two within-subject variables: Release time and Context. Release time consisted of two levels: short and long. Context contained three levels: high, medium, and low, corresponding to the BKB-SIN, the AFAAF, and the WIN tests. The between-subject variable, Group, had two levels: low and high cognitive performance.

As described earlier, the statistical analyses were originally planned for 34 subjects, which provided 80.7% power ($\alpha = 0.05$) to detect a medium effect of the interaction between cognitive group and release time for one speech recognition test. The grouping strategy ultimately employed in this study resulted in inclusion of a smaller number of subjects. However, the resulting groups were very different in terms of participants’ cognitive abilities, which in fact increased the possibility of observing a difference in speech recognition performance. In addition, the full model ANOVA included data from more than one speech recognition test, resulting in higher power. Therefore, the statistical power was maintained for the full model ANOVA.

An overview of the analysis results of the full model ANOVA is listed in Table 6. In reviewing the main effects of the three variables (Group, Release time, and Context), the results showed no significant main effect for Group ($F(1,27) = 3.119$, $p = 0.089$) or Release time ($F(1,27) = 1.055$, $p = 0.313$). However, the main effect of Context was statistically significant ($F(2,54) = 826.004$, $p < 0.001$).

Table 6

Summary of the Full Model ANOVA

Source	*df*	*F*	*p*
	Between subjects		
Group (A)	1	3.119	0.089
Error	27	(36.105)	
	Within subjects		
Release time (B)	1	1.055	0.313
B×A	1	4.023	0.055
B within group error	27	(1.508)	
Context (C)	2	826.004	<0.001
C×A	2	0.079	0.924
C within group error	54	(5.861)	
B×C	1.609 [a]	0.131 [a]	0.834 [a]
B×C×A	1.609 [a]	3.303 [a]	0.056 [a]
B×C within group error	43.448 [a]	(2.286 [a])	

Note. Values enclosed in parentheses represent mean square errors.

[a] *with Greenhouse-Geisser adjustment*

Based on the a priori research questions, it is of interest to examine the interaction effects to explore the relationship among the three variables. The purpose of the present research was to explore the relationship between cognitive abilities and aided speech recognition performance with short and long release times when speech recognition tests with different amounts of linguistic context were used. This relationship was explored by examining the following relationships:

(1) The relationship between cognitive abilities and speech recognition performance with short and long release times regardless of linguistic context (Cognitive abilities and Release time);

(2) The relationship between cognitive abilities and speech recognition performance with short and long release times for speech recognition tests with different amounts of linguistic context (Cognitive abilities and Release time considering Linguistic context);

(3) The relationship between release time and speech recognition performance when tests with different amounts of linguistic context are used (Release time and Linguistic context);

(4) The relationship between release time and speech recognition performance for low and high cognitive groups when tests with different amounts of linguistic context are used (Release time and Linguistic context considering cognitive abilities).

Relationship 1: Cognitive Abilities and Release Time

In order to examine this relationship, the two-way interaction shown in Table 6 between Cognitive group and Release time was examined. Figure 10 depicts the relationship between cognitive group and release time combining the three levels of context. It is seen that low cognitive abilities were associated with better performance using long release times, while high cognitive abilities were associated with better performance using short release times. Statistical analyses from the full model ANOVA showed that this interaction effect was close to the significance level of 0.05 ($F(1,27) = 4.023$, $p = 0.055$). Post-hoc pairwise comparisons (least significant difference test) revealed (1) a marginally significant effect that the participants with high cognitive abilities performed better with a short release time than with a long release time ($p = 0.051$), and (2) a significant effect that the participants in the high cognitive group performed better than those in the low cognitive group when using the short release time ($p = 0.042$).

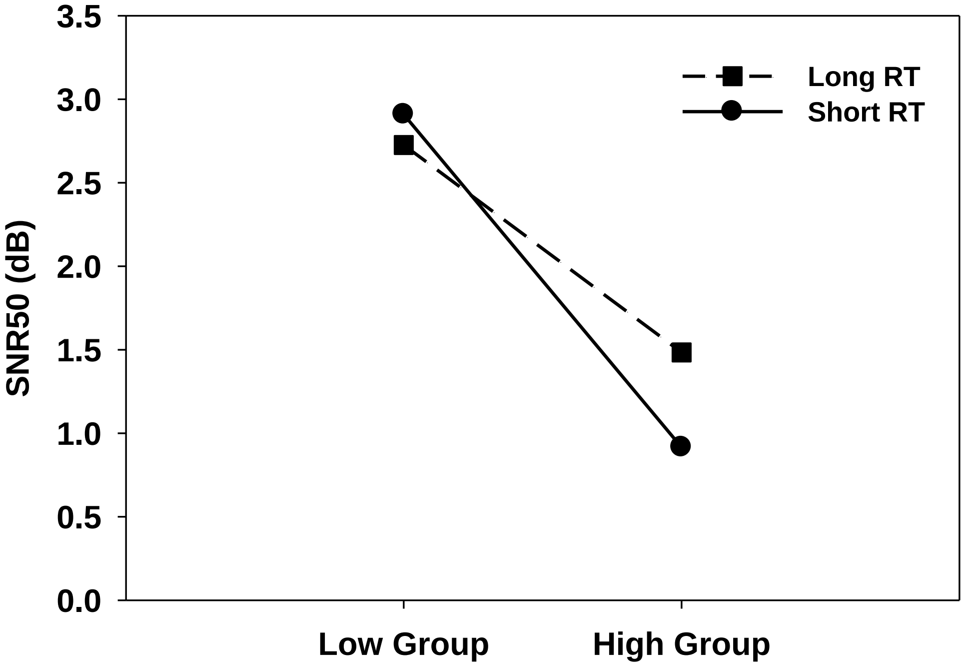

Figure 10. Interaction between release time and cognitive performance group regardless of linguistic context. Note that the lower the SNR, the better the performance.

Relationship 2: Cognitive Abilities and Release Time Considering Linguistic Context

In order to examine this relationship, a three-way interaction between Release time, Context, and Group was evaluated in the full model ANOVA. The analysis for this three-way interaction was adjusted for failing to meet the assumption of Sphericity (Table 6). The Greenhouse-Geisser adjusted results showed that this three-way interaction was close to significant at a 0.05 level ($F(1.609,43.448) = 3.303$, $p = 0.056$). One way to decompose a three-way interaction is to assess the interaction effect of two variables at each level of the third one. Since the relationship in question was about release time and cognitive abilities, the interaction between Release time and Group was examined for each level of Context (Figure 11). A mixed model repeated measure ANOVA was performed for each speech recognition test to examine this interaction effect. In this model, release time was the within-subject variable (two levels) and cognitive group was the between-subject variable (two levels).

First, the main effect of release time was examined. Table 7 shows the mean SNR50 scores for the short and the long release times. It is seen that the mean SNR50 score for the short release time was slightly lower (better) than that for the long release time for each speech recognition test. However, the main effect of release time was not statistically significant for the AFAAF ($F(1,27) = 0.483$, $p = 0.493$), the BKB-SIN ($F(1,27) = 0.215$, $p = 0.647$), or the WIN($F(1,27) = 0.247$, $p = 0.623$).

Table 7

Mean SNR50 (dB) for the Short and the Long Release Times. Values Enclosed in Parentheses Represent One Standard Deviation (N = 29).

	Release time	
	Short	Long
AFAAF	-7.17 (3.04)	-6.83 (2.56)
BKB-SIN	1.62 (2.21)	1.72 (2.14)
WIN	11.30 (3.40)	11.42 (4.09)

Second, the main effect of cognitive group was examined. Table 8 shows the mean SNR50 scores for the low and the high cognitive groups. It is seen that the mean SNR50 score for the high cognitive group was lower (better) than that for the low cognitive group for each speech recognition test. Statistical analyses showed a marginally significant main effect of cognitive group for the AFAAF ($F(1,27) = 3.876$, $p = 0.059$) and the BKB-SIN ($F(1,27) = 4.167$, $p = 0.051$). However, the main effect of cognitive group was not statistically significant for the WIN ($F(1,27) = 1.128$, $p = 0.298$).

Table 8

Mean SNR50 (dB) for the Two Cognitive Performance Groups. Values Enclosed in Parentheses Represent One Standard Deviation.

	Cognitive performance group	
	Low	High
AFAAF	-6.10 (2.47)	-7.91 (2.47)
BKB-SIN	2.46 (2.07)	0.88 (2.07)
WIN	12.09 (3.68)	10.63 (3.68)

Last, the interaction effect between cognitive group and release time was examined for each speech recognition test in two ways: (1) the mean SNR50 scores for the two groups with both the short and the long release times for each speech recognition test (Figure 11), and (2) the mean SNR50 difference between the two groups for each speech recognition test with each release time (Figure 12). The mean difference scores showed in Figure 12 were calculated as the mean SNR50 value for the low cognitive group minus the mean SNR50 value for the high cognitive group. Therefore, a positive value indicated better speech recognition performance for the high cognitive group, while a negative value indicated better speech recognition performance for the low cognitive group.

The analysis results of the interaction effect between cognitive group and release time for each speech recognition test are reported as the following.

For the AFAAF, descriptive statistics revealed that the participants with low cognitive abilities showed better speech recognition performance with the long release time, whereas the participants with high cognitive abilities showed better speech recognition performance with the short release time (Figure 11a). This interaction was statistically significant ($F(1, 27) = 4.499$, $p = 0.043$). Post-hoc pairwise comparison analyses exploring this interaction effect revealed that (1) speech recognition performance between the two release time settings was not statistically significant for either group; (2) the participants with high cognitive abilities performed significantly better than those with low cognitive abilities only when short release time was used ($p = 0.018$) (see Figure 12). Therefore, this significant interaction effect was a result of group difference with the short release time. The observed pattern for the AFAAF (Figure 11a) is in fact the same as the pattern reported by Gatehouse et al. (2003).

For the BKB-SIN, descriptive statistics revealed the same pattern as the AFAAF, in which the participants with low cognitive abilities showed better speech recognition performance with the long release time, whereas the participants with high cognitive abilities showed better speech recognition performance with the short release time (see Figure 11b). However, the interaction effect between cognitive group and release time was not statistically significant ($F(1, 27) = 2.196$, $p = 0.150$). When examining the difference between groups for the two release times, the participants with high cognitive abilities performed significantly better than those with low cognitive abilities when the short release time was used ($p = 0.027$) (see Figure 12).

By contrast, for the WIN, descriptive statistics revealed that the participants with low cognitive performance showed better performance with the short release time, whereas their counterparts with high cognitive performance showed almost no difference in performance between the two release times (Figure 11c). However, the interaction effect between cognitive group and release time and was not statistically significant ($F(1, 27) = 1.001$, $p = 0.326$). Moreover, the participants in the two cognitive groups did not have significantly different speech recognition performance on this test no matter what release time processing was used (Figure 12).

In summary, the analysis results revealed that the short and the long release times did not yield significantly different speech recognition performance for either cognitive group no matter what speech recognition test was used. However, with the AFAAF and the BKB-SIN, significant differences between the two cognitive groups were observed when the short release time was used, and this produced the appearance of a relationship between cognitive abilities and speech understanding with different release times, especially for the AFAAF test.

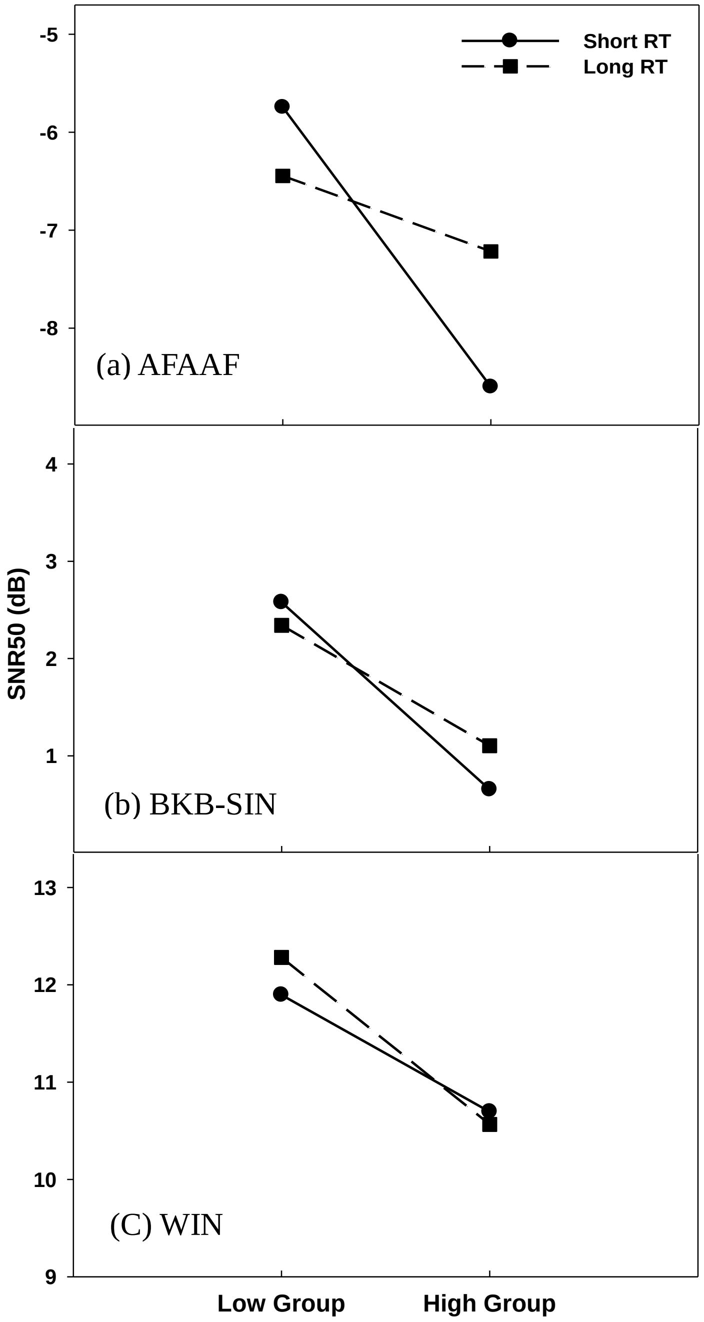

Figure 11. Relationship between release time and cognitive groups when using each of the three speech recognition tests. Note that the lower the SNR, the better the performance.

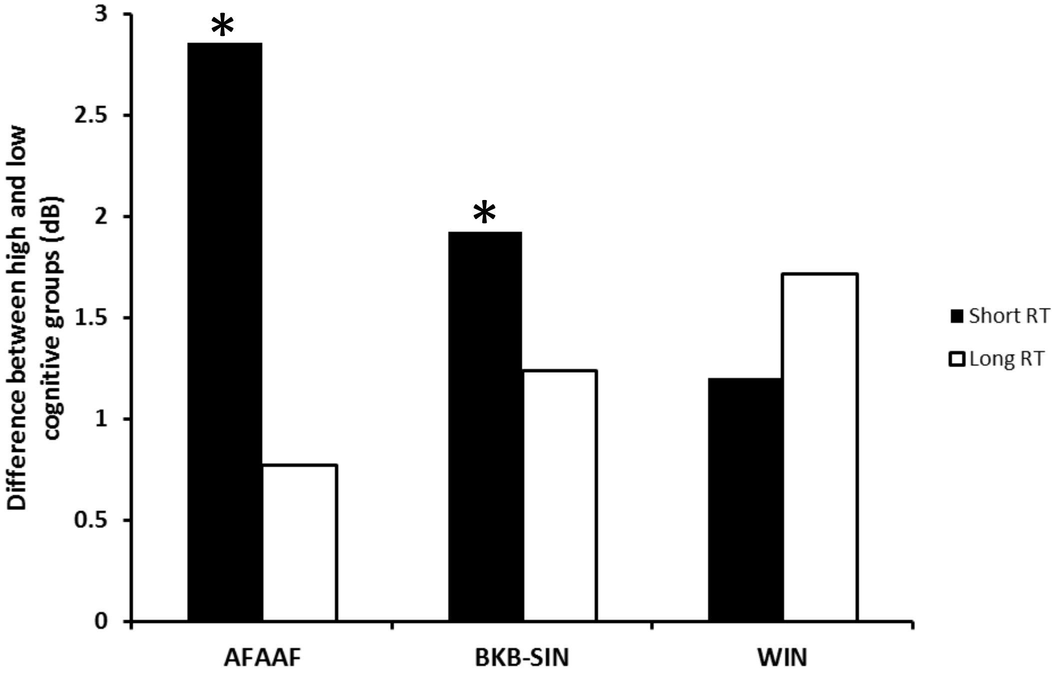

Figure 12. Mean SNR50 difference between the low and the high cognitive performance groups for each speech recognition test with each release time. Asterisks indicate statistically significant differences ($p < 0.05$).

Relationship 3: Release Time and Linguistic Context

In order to examine this relationship, the two-way interaction shown in Table 6 between Release time and Context was examined. The descriptive data for this analysis are given in Table 7 and plotted in Figure 13. From Figure 13, it is seen that the mean SNR50 scores for the short and the long release times were very similar for each of the three speech recognition tests. In the full model ANOVA, statistical analyses showed that the two-way interaction effect between Release time and Context was not significant ($F(1.609\ 43.448) = 0.131$, $p = 0.834$), suggesting that the two release times did not yield different speech recognition performance with any of the three tests. Therefore, in the present study, hearing aid users as a group did not have significantly different speech recognition performance between the short and the long release times.

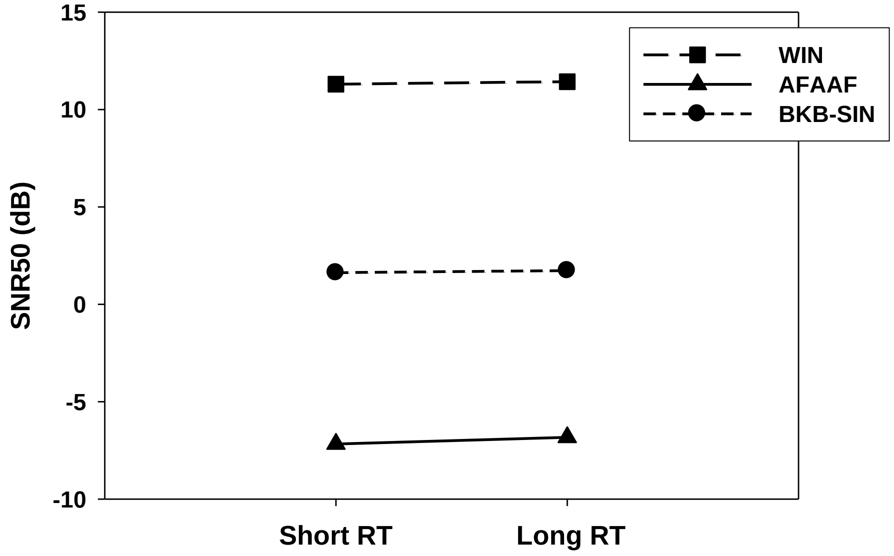

Figure 13. Relationship between release time and speech understanding for each test regardless of cognitive performance. Note that the lower the SNR, the better the performance.

Relationship 4: Release Time and Linguistic Context Considering Cognitive Abilities

To examine this relationship, the two-way interaction between Release time and Context was examined for each cognitive group. A within-subject design ANOVA was conducted for each of the two cognitive groups. Both Release time (two levels) and Context (three levels) were the within-subject variables. Descriptive data for the two-way interaction analysis are plotted in Figure 14 (a-b) for the two cognitive groups. It can be seen that the mean SNR50 scores for the short and the long release times were similar for each speech recognition test. The Statistical analyses from the within-subject design ANOVA showed that the two-way interaction effect between Release time and Context was not significant for the high cognitive group ($F(1.219, 43.448) = 2.719$, $p > 0.05$) or the low cognitive group ($F(2, 43.448) = 1.042$, $p > 0.05$). The results suggested that none of the speech recognition tests produced a significantly different performance between the short and the long release times for either cognitive group.

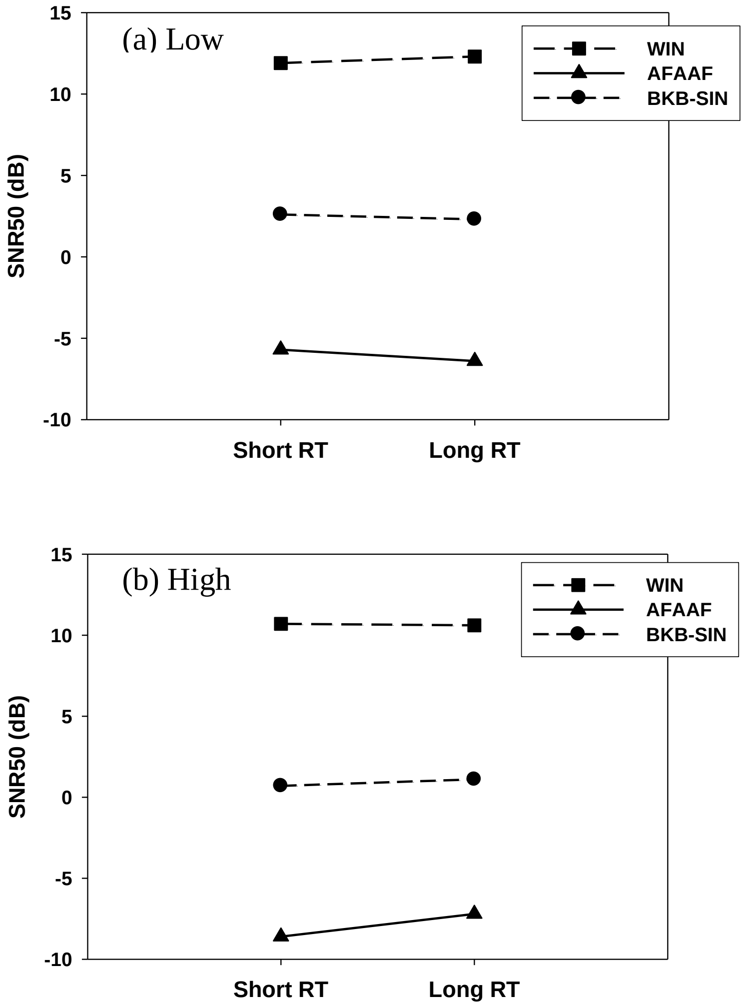

Figure 14. Relationship between Release time and Context for (a) the low cognitive group and (b) the high cognitive group. Note that within a test, the lower the SNR, the better the performance.

Chapter 5

Discussion

The existing research has provided support for the effects of compression release time setting on aided speech recognition performance and has examined the benefits of using short and long release times. While the results of many studies do not show a significant difference in performance with short and long release times (e.g., Bentler & Nelson, 1997; Gilbert et al., 2008), some studies reported more benefits with one type of release time in terms of perceived sound quality, clarity, and pleasantness (Hansen, 2002; Neuman et al., 1995,1998). However, the release time that should be prescribed for hearing aid users remains unclear. Recent research has established a connection between release time and hearing aid users' cognitive abilities (Gatehouse et al., 2003; Lunner, 2003). Gatehouse et al. (2003) concluded that hearing aid users with greater cognitive abilities performed better with short release times when they were tested in modulated background noises, while hearing aid users with poorer cognitive abilities performed better with long release times when they were tested in unmodulated background noises. While Lunner and Sundewall-Thoren (2007) supported this finding, Foo et al. (2007), Rudner et al. (2009), and Cox and Xu (2010) did not. In reviewing the inconsistent findings across these studies, Cox and Xu (2010) noticed that previous research used different types of speech recognition tests. They hypothesized that linguistic context of speech recognition test materials is one of the factors that could possibly account for such inconsistencies. The purpose of this study was to extend this line of research by examining the effect of linguistic context on the relationship between cognitive abilities and release time. Three speech recognition tests with different amounts of linguistic context were incorporated in the present study in an attempt to test the hypothesis proposed by Cox and Xu (2010). In addition, the Gatehouse et al. (2006b) study was replicated in an attempt to explore why some studies supported their findings (e.g., Lunner & Sundewall-Thoren, 2007) while other studies did not (e.g., Cox & Xu, 2010; Foo et al., 2007).

The present study advanced this line of research in terms of its application to current technology hearing aids. Previous studies that examined the relationship between hearing aid users' cognitive abilities and release time (Cox & Xu, 2010; Foo et al., 2007; Gatehouse et al., 2003, 2006b; Lunner & Sunderwall-Thoren, 2007; Rudner et al., 2009) used the same hearing aid technology from the same manufacturer. These hearing aids had two compression channels with the nominal short and long release time settings at 40 msec and 640 msec, respectively. The present study used hearing aids with newer technologies from a different manufacturer using a different processing chip. The hearing aids used in the present study had 12 compression channels with the nominal short and long release time settings at 50 msec and 2000 msec, respectively. The present study is the only known study that used different hearing aid technologies from a different manufacturer to assess the relationship between cognitive abilities and release time. The results of the present study, together with the findings reported from the previous studies, make this line of investigation more generalizable across different hearing aids.

Replication of Gatehouse et al. (2006b) Study

Gatehouse and colleagues reported a significant correlation of 0.30 between hearing aid users' cognitive abilities and speech recognition benefit of short over long release time (Benefit-ShortRT) (Gatehouse et al., 2006b). Based on this finding, they suggested a connection between cognitive abilities and speech recognition performance with different release time processing (Gatehouse et al. 2003, 2006b). They suggested that hearing aid users with higher cognitive abilities had better speech recognition performance with short release time processing. This finding was bolstered by a later study, in which Lunner and Sunderwall-Thoren (2007) examined the same correlation using a speech recognition test in a different language. However, no other study has substantiated this relationship. Cox and Xu (2010) conducted the same correlation analyses on data obtained using a different speech recognition test and a different method to quantify cognitive abilities. Their findings were not in line with Gatehouse's study.

In order to replicate Gatehouse's study and allow a parallel comparison with the previous studies, the present study adopted the same correlation analyses for each of the three speech recognition tests. Despite the fact that the correlation analyses in the present study were not statistically significant (due to the smaller number of participants), the correlation coefficients were essentially the same magnitude as those reported in Gatehouse et al.'s (2006b) study when using the AFAAF. It is worth noting that the AFAAF is essentially equivalent to the FAAF which was used in Gatehouse et al.'s (2003, 2006b) study. Therefore, the present study replicated the results of Gatehouse et al. (2006b) using an equivalent speech recognition test.

Speech Recognition Performance of Listeners with Different Cognitive Abilities

Previous research has suggested that higher cognitive abilities are associated with better speech understanding performance (e.g., Lunner, 2003). However, this association was not observed in all studies about cognitive ability and speech understanding. This inconsistency has also been found in previous studies examining the relationship between cognitive abilities and aided speech recognition with different release times. Lunner and Sunderwall-Thoren (2007) reported a significant main effect of cognitive group, showing that the cognitively high performing group had significantly better speech recognition performance compared to the cognitively low performing group. However, Gatehouse et al. (2003) and Rudner et al. (2009) did not find the main effect of cognitive group. It is worth noting that the three previous studies used the same cognitive test to quantify hearing aid users' cognitive abilities, but used different speech recognition tests to evaluate their aided speech recognition performance. Using different speech recognition tests in previous research was one factor that was suspected to partially account for these observations.

The present study did not find a significant main effect of cognitive group in the full model ANOVA (Table 6), suggesting that the high cognitive group was not significantly different from the low cognitive group in aided speech recognition performance, regardless of speech recognition test. However, further analyses of each speech recognition test revealed marginal significant main effects of cognitive group with the AFAAF and the BKB-SIN (Table 8), indicating that hearing aid users with high cognitive abilities have better speech recognition performance compared to their counterparts with low cognitive abilities. This finding supports the suspicion based on the findings from the previous studies that speech recognition tests influence the main effect of cognitive group. The findings from the present study, together with the previous studies, suggest that the effect of cognitive ability on speech recognition performance might depend upon the chosen speech recognition test, at least to some extent.

Relationship between Cognitive Abilities and Speech Recognition with Short and Long Release Times

The present study examined the interaction effects between cognitive abilities, release time, and linguistic context to explore the relationship between cognitive abilities and aided speech recognition performance in noise with different release times. The results of the interaction between cognitive ability and release time indicated that hearing aid users with high cognitive abilities performed better with a short release time than with a long release time, irrespective of speech recognition test (Table 6 and Figure 10). However, the present study found no significant effect of release time on speech recognition performance for either cognitive group with any of the three tests (Figure 11). In addition, the results of the interaction between linguistic context and release time showed that hearing aid users as a group did not have significantly different speech recognition performance between the short and the long release times when using any of the three tests (Figure 13). Moreover, none of the speech recognition tests produced significantly different performance between the two release times for either cognitive group (Figure 14).

Although the results indicated no significant effects of release time on speech recognition performance for either cognitive group and for each speech recognition test, speech recognition performance seemed to be better with the short rather than long release time for hearing aid users with high cognitive abilities when using the AFAAF and the BKB-SIN (Figure 11). However, no clear pattern was noted for hearing aid users with lower cognitive abilities. Moreover, hearing aid users with high cognitive abilities performed significantly better than did their counterparts with low cognitive abilities when using short release time processing (Figure 12). This pattern was observed for the AFAAF and the BKB-SIN but not for the WIN.

The findings from the present study indicated that higher cognitive abilities were associated with better speech recognition performance with shorter release time processing. This pattern was consistent with the findings reported by Gatehouse et al. (2003, 2006b) and Lunner and Sunderwall-Thoren (2007) for hearing aid users with high cognitive abilities. Lunner and Sunderwall-Thoren (2007) suggested that hearing aid users with higher cognitive abilities were able to process and comprehend speech information in complex listening conditions with large fluctuations in masking noise and hearing aid signal processing. However, the observed pattern from the present study contradicted the findings reported by Cox and Xu (2010) and Foo et al. (2007). In these two studies, advantageous release time processing was associated only with lower cognitive abilities (Table 1). It is worth noting that the pattern obtained from the present study was observed only when using the AFAAF and the BKB-SIN but not the WIN. Moreover, this pattern was most evident for the AFAAF. This suggested that the association between high cognitive abilities and short release time processing holds only when using certain types of speech recognition tests. Thus, the assessment of the relationship between cognitive abilities and speech understanding with different release time processing depends largely on the characteristics of the speech recognition tests.

To examine this factor, the present study incorporated three speech recognition tests with different amounts of linguistic context. The BKB-SIN and the WIN are both open-set tests categorized as the context-high and the context-low tests, respectively. The BKB-SIN is a sentence test and allows for a substantial top-down processing to understand words and sentences. However, the WIN is a word-based test. Listeners must rely on bottom-up processing to understand the test words because the linguistic context in the WIN is limited. The AFAAF is very different from the BKB-SIN and the WIN. First, it is a closed-set word-based test with a fixed carrier phrase. Second, the displayed alternatives differ in one or two phonological features (minimal pair), which can be very confusing. Considering the characteristics of the AFAAF, it is assumed that some predictive cues from the displayed alternatives are available to listeners to assist in speech recognition. Therefore, in the planning phase of the present study, the AFAAF was considered an intermediary between the BKB-SIN and the WIN in terms of linguistic context. Assuming an effect of linguistic context on the relationship between cognitive abilities and release time, speech recognition performance with the three tests should reveal a pattern that would follow the order of the amount of linguistic context. However, the findings from the present study did not show such pattern. Instead, the AFAAF and the BKB-SIN showed the same pattern regarding the relationship between cognitive abilities and speech understanding with short and long release times while the WIN showed a pattern that was opposite to the other two speech recognition tests. It is also interesting that the AFAAF produced the greatest effect on the difference between the two cognitive groups. Moreover, the BKB-SIN did not differ substantially from the WIN in patterns of speech recognition performance in terms of the factors of cognitive ability and release time (See Figure 11).

The AFAAF and the BKB-SIN produced similar speech recognition patterns, suggesting that these two tests affected the relationship between cognitive abilities and speech understanding with different release times the same way. This is probably because both speech recognition tests allow top-down processing to facilitate speech understanding in addition to audibility. For the BKB-SIN, the top-down processing is involved probably because of its context-rich test sentences. Regarding speech recognition, working memory is a capacity-limited system that both stores recent phonological information in short-term memory and simultaneously processes the information with knowledge stored in long-term memory. With the BKB-SIN, working memory capacity is linked to speech understanding. However, since the contextual cues are involved in speech understanding, release time might become less important (Cox & Xu, 2010). The AFAAF engages top-down processing via a certain amount of predictive cues from displayed alternatives. Notably, the AFAAF produced the greatest effect on the difference between the two cognitive groups. This suggests that the AFAAF has some other unique characteristics in addition to linguistic context, which make it sensitive to difference in cognitive abilities. This might also explain why Gatehouse's study, which used the FAAF, could not be replicated by some similar studies. Later sections offer further discussion about the characteristics of the AFAAF.

In contrast to the AFAAF and the BKB-SIN, the WIN is an open-set monosyllabic word test that has limited linguistic context. Understanding the test words masked by noise mostly relies on audibility. Thus, speech recognition is mainly based on bottom-up processing. Consequently, cognitive abilities might not be involved as much as with the other two speech recognition tests. It is interesting that the short and the long release time processing did not reveal substantial and statistically significant differences in speech recognition performance for either group for both the WIN and the BKB-SIN (Figures 11b and 11c). This implies that a hearing aid user's speech recognition performance in noise with different release time settings probably does not depend on linguistic context of speech recognition test material. Thus, it can be argued that linguistic context of speech recognition tests might not be considered a critical factor in assessing the relationship between cognitive abilities and understanding speech with different release times. The results from the present study do not support the hypothesis proposed by Cox and Xu (2010). It is reasonable to speculate that other factors embedded in speech recognition test influence the assessment of the relationship of interest.

What Makes the AFAAF a Sensitive Test to Detect Cognitive Difference?

The AFAAF was introduced in the Method chapter. Briefly, the AFAAF is a word-based closed-set test. Fundamental and underlying differences exist between open-set and closed-set tests, in addition to chance performance and the way the two types of tests are administered. Clopper, Pisoni, and Tierney (2006) suggested that crucial differences between the two test formats are due to the nature of the specific task demands imposed on lexical access of phonetically similar words. In open-set tests, listeners must compare the target word to all possible candidate words in their lexical memories, whereas in closed-set tests, the listeners only need to make a limited number of comparisons using the provided options. Therefore, the difference in task demand of the two test formats is, in essence, due to differences in lexical competition effect.

At first glance, it seems obvious that recognizing the same words requires more word comparisons in open-set tests compared to closed-set tests. As a result, open-set tests are more difficult compared to closed-set tests. However, lexical competition in closed-set tests could increase if the degree of confusion between response alternatives increased (Clopper et al., 2006). According to Clopper et al. (2006), greater phonetic confusability among the response alternatives is associated with greater lexical competition in a closed-set test because it requires an effort from a listener to differentiate subtle phonetic differences.

Phonemes are confusable when they are phonologically similar. When the task is to distinguish the target item from a number of phonologically similar items, the probability of losing a phonological feature, which discriminates the target item from other items of the memory set, will be greatest when the number of discriminating features is small (Salamé & Baddeley, 1982). For example, it is difficult to distinguish the target word from the given minimal pair of response alternatives because only one or two phonemes differentiate a pair of words. Comparing phonologically similar words can affect short-term memory (STM). Evidence shows that the similarity between phonemes leads to STM confusions of English vowels and consonants (Wicklegren, 1965, 1966).

In addition to confusable phonemes, visual information about the displayed response alternatives is stored in a listener’s short-term memory for comparison. It has been proposed that this visual information relates to a listener’s cognitive ability, although there is little direct evidence to support this proposition. Previous research on visual word recognition shed some light on this subject. Gathercole and Baddeley (1993) reviewed studies on visual word recognition performance and suggested an association with working memory when certain types of word recognition tasks (e.g., rhyme judgment) are required. Comparing two phonological representations requires information storage, which can impose a substantial memory load.

As introduced in earlier chapters, working memory includes short-term memory and other processing mechanisms that help make use of short-term memory (Baddeley & Hitch, 1974; Cowan, 2008). The confusion induced by similar phonemes in short-term memory could potentially influence the function of working memory. In addition, reading phonologically similar response alternatives might increase a hearing aid user's working memory load. Therefore, since working memory is one aspect of cognitive processing (Baddeley & Hitch, 1974), it is likely to be heavily involved in distinguishing the target word from the non-target alternatives when they are phonologically similar to each other. Therefore, it is reasonable to argue that listeners with higher cognitive abilities could differentiate similar phonemes and identify the target words more accurately compared to their counterparts with lower cognitive abilities.

According to the above discussion, among the three speech recognition tests in the present study, the AFAAF appears to be the most sensitive test in detecting differences in cognitive ability. One of the reasons is that the four alternatives on the test are constructed based on a minimal pair structure while the alternatives are very similar in terms of phonemes. Thus, the lexical competition aimed at differentiating subtle phonological differences between target words and the corresponding non-target alternatives is high. This requires higher cognitive capability to process the confusable lexical information stored in short-term memory. Moreover, the minimal pair structure for the alternatives also makes storage and comparison of the displayed alternatives demanding, requiring higher cognitive ability. Consequently, when using the AFAAF, speech recognition performance could be considerably better among listeners with higher cognitive abilities.

Because the BKB-SIN and the WIN are two open-set tests, listeners are required to compare the target words to all possible candidate words in their lexical memories. These two tests differ substantially in their amount of linguistic context. For the BKB-SIN, it is probable that the effect of linguistic context overcomes the effect of lexical competition, as the linguistic context is substantial. In contrast, the WIN has limited linguistic context and the lexical competition is truly determined based on the comparisons with the listener's lexical memory. Therefore, in the present study, it is not appropriate to classify the AFAAF as an intermediary test among the three speech recognition tests in terms of linguistic context. It is clear that the AFAAF is very different from the other two tests.

What Release Time should be Prescribed?

One of the clinically relevant questions that remains unclear is what compression release time, a shorter one or a longer one, should be prescribed for hearing aid users. Previous research has suggested that a hearing aid user's cognitive ability is one possible predictor, which can assist clinicians in selecting an appropriate compression release time. However, the results were not consistent. Some previous studies suggested shorter release times for hearing aid users with high cognitive abilities (Gatehouse et al., 2003, 2006b; Lunner & Sunderwall-Thoren, 2007) while other studies did not show significant differences in performance between the two release times in the same population (Cox & Xu, 2010; Foo et al., 2007). There is no consensus on the more advantageous release time for hearing aid users with low cognitive abilities.

The present study contributes to the small body of literature on this subject. The results failed to indicate statistically significant benefits with short or long release time for either cognitive group. When using the AFAAF and the BKB-SIN, hearing aid users with higher cognitive abilities might benefit slightly from short release time processing. However, this pattern was not observed when using the WIN. Because of the inconsistent results from the three speech recognition tests in the present study, it is not possible to make a recommendation about what release time should be prescribed. At this moment, either a short or a long release time could be prescribed for hearing aid users, regardless of their cognitive abilities. Nonetheless, this recommendation is still open to debate. The results from the present study suggest that the selection of the most advantageous release time for a given hearing aid user might be dependent on factors other than cognitive ability.

Chapter 6

Summary and Conclusions

Difference in speech recognition performance with short and long release time processing has been noted in previous research. Recent research has established a connection between hearing aid users' cognitive abilities and release time (e.g., Gatehouse et al., 2003). Researchers hope to use cognitive ability as a predictor of release time selection. The results from these previous studies about the relationship between cognitive ability and speech understanding with different release times have been contradictory. Cox and Xu (2010) suspected that linguistic context of speech recognition test materials was one of the factors that accounted for the inconsistency. For this reason, the factor of linguistic context was taken into consideration in the present study. The goal of the study was to examine the relationship between hearing aid users' cognitive abilities and their aided speech recognition performance with short and long release time using speech recognition tests with different amounts of linguistic context.

Thirty-four experienced hearing aid users participated in the present study. Their cognitive abilities were quantified using a reading span test. Digital WDRC BTE hearing aids with adjustable release time settings were bilaterally fitted to all participants. Their aided speech recognition performance was evaluated using three tests with different amounts of linguistic context (the WIN, the AFAAF, and the BKB-SIN). There was no acclimatization period prior to testing. Percentage correct scores were collected at a number of predetermined SNRs using each speech recognition test. For each subject, a psychometric function was fit to the discrete scores for each release time and each speech recognition test. SNR50 values obtained from the psychometric functions were used as the performance measure for comparisons.

Regarding the correlation between hearing aid users' cognitive abilities and speech recognition benefit of short over long release time, the present study replicated the results of Gatehouse et al. (2006b) using an equivalent speech recognition test. The results from the present study also showed that hearing aid users with high cognitive abilities performed better on the AFAAF and the BKB-SIN compared to those with low cognitive abilities when using short release time processing (Figure 12). Irrespective of speech recognition test, hearing aid users with high cognitive abilities performed better with a short release time than with a long release time (Figure 10). However, significant differences between release times for each cognitive group were not obtained for any of the three speech recognition tests (Figure 11). That is to say, an effect of linguistic context on the relationship between cognitive abilities and speech understanding with short and long release times was not observed. This finding did not support the hypothesis of Cox and Xu (2010) that linguistic context of speech recognition test materials might partially account for the contradictory results reported in previous studies.

The present study highlights the impact of using different speech recognition tests for evaluating aided speech recognition performance with short and long release times in association with cognitive abilities. In the current study, hearing aid users with high cognitive abilities performed significantly better than those with low cognitive abilities when using the short release time. This pattern was observed for the AFAAF and the BKB-SIN but not for the WIN. Moreover, this pattern was more evident for the AFAAF. When comparing the three speech recognition tests used in the present study, the AFAAF was found to be the most sensitive to differences in cognitive ability. The reason for this sensitivity is unclear and there was no direct evidence to explain this finding. Following a review of the three speech recognition tests used in the present study, characteristics of the AFAAF, such as the closed-set test format and the minimal pair structure of the response alternatives, were suspected of being partly responsible for this observation. Correlational evidence was examined in an attempt to provide possible explanations for the sensitivity of the AFAAF to differences in cognitive ability. Several aspects of the AFAAF are discussed. Phonological similarity between response alternatives and having visual access to response alternatives are two main factors that might closely relate the AFAAF to a hearing aid user's cognitive ability. This might also explain why Gatehouse's study, using the FAAF, could not be replicated by some similar studies.

The present study contributes to the growing body of research on assessment of the relationship between hearing aid users' cognitive abilities and their speech recognition performance with short and long release times. Results showed that none of the speech recognition tests produced significantly different performance between the short and the long release times for either cognitive group (Figure 14). Regarding a recommendation of prescribed release time, it is argued that either a short or a long release time could be prescribed for hearing aid users regardless of their cognitive abilities because the obtained SNR differences in the present study between the two release time settings were small and probably not clinically important. This recommendation is open to debate.

Results from the present study suggest that cognitive ability is associated with speech understanding in noise for hearing aid users, but it might not be important in prescribing release time. In addition, there might be some other factors affecting the advantage of using short and long release times. Future research should focus on exploring other predictors to assist in release time prescription.

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Appendix A: Determine Compression Ratios for Hearing Aid Fitting

(1) <u>Sloping loss</u> CT: compression threshold; CR: compression ratio; S: short RT; L: long RT; AT: attack time; RT: release time

Hearing loss	**250Hz**	**500Hz**	**1kHz**	**2kHz**	**4kHz**	**8kHz**
	15	**30**	**60**	**80**	**70**	**75**

	200Hz	**500Hz**	**1kHz**	**1.5kHz**	**2kHz**	**2.5kHz**	**3kHz**	**3.5kHz**	**4kHz**	**4.5kHz**	**5kHz**	**6kHz**
CT	**43**	**46**	**37**	**32**	**29**	**26**	**24**	**23**	**22**	**21**	**19**	**18**

200Hz		**CR**	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**	**2**	**2.1**	**2.2**	**2.3**	**2.4**	**2.5**	**2.6**	**2.7**	**2.8**	**2.9**	**3**
	S	AT	17.5	15	20	15	20	15	157.5	NA	405	365	NA	450	NA	NA	380	NA	462.5	NA	NA	NA
		RT	197.5	1985	770	1228	587.5	1943	1983	NA	1945	1648	NA	1878	NA	NA	1738	NA	1825	NA	NA	NA
	L	AT	397.5	225	32.5	60	325	165	205	NA	280	305	NA	340	NA	NA	285	NA	445	NA	NA	NA
		RT	1975	1963	1993	1993	1958	1958	1980	NA	1888	1520	NA	1988	NA	NA	1918	NA	1765	NA	NA	NA

500Hz		CR	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**	**2**	**2.1**	**2.2**	**2.3**	**2.4**	**2.5**	**2.6**	**2.7**	**2.8**	**2.9**	**3**
	S	AT	10	25	35	40	55	60	80	60	NA	80	NA	100	NA	NA	90	NA	NA	90	NA	NA
		RT	15	15	35	15	15	15	15	105	NA	60	NA	60	NA	NA	40	NA	NA	90	NA	NA
	L	AT	10	10	15	25	30	35	30	30	NA	35	NA	35	NA	NA	35	NA	NA	40	NA	NA
		RT	470	225	270	415	645	600	680	405	NA	805	NA	675	NA	NA	785	NA	NA	685	NA	NA

1kHz		CR	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**	**2**	**2.1**	**2.2**	**2.3**	**2.4**	**2.5**	**2.6**	**2.7**	**2.8**	**2.9**	**3**
	S	AT	10	12.5	20	30	30	35	35	37.5	NA	32.5	40	NA	45	NA	NA	45	NA	47.5	NA	NA
		RT	65	65	75	82.5	90	80	85	77.5	NA	90	85	NA	95	NA	NA	95	NA	112.5	NA	NA
	L	AT	10	10	17.5	25	37.5	42.5	45	47.5	NA	45	47.5	NA	52.5	NA	NA	52.5	NA	62.5	NA	NA
		RT	180	397.5	625	775	935	890	910	1135	NA	1575	1170	NA	1040	NA	NA	1348	NA	1165	NA	NA

1.5kHz		CR	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**	**2**	**2.1**	**2.2**	**2.3**	**2.4**	**2.5**	**2.6**	**2.7**	**2.8**	**2.9**	**3**
	S	AT	10	10	15	20	25	25	30	30	25	NA	30	NA	30	25	NA	NA	30	NA	25	NA
		RT	150	60	60	70	70	75	80	75	85	NA	85	NA	80	85	NA	NA	90	NA	90	NA
	L	AT	10	10	15	25	30	30	35	35	35	NA	30	NA	30	35	NA	NA	35	NA	30	NA
		RT	185	365	530	645	705	670	740	800	755	NA	845	NA	795	835	NA	NA	760	NA	785	NA

2kHz		CR	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**	**2**	**2.1**	**2.2**	**2.3**	**2.4**	**2.5**	**2.6**	**2.7**	**2.8**	**2.9**	**3**
	S	AT	13.75	17.5	22.5	28.75	25	26.25	23.75	25	NA	30	25	22.5	NA	26.25	NA	25	NA	NA	20	NA
		RT	17.5	45	43.75	65	70	71.25	75	70	NA	63.75	57.5	75	NA	96.25	NA	85	NA	NA	1038	NA
	L	AT	8.75	16.25	25	25	31.25	36.25	40	43.75	NA	32.5	27.5	35	NA	26.25	NA	26.25	NA	NA	27.5	NA
		RT	12.5	43.75	185	226.3	672.5	591.3	1005	882.5	NA	547.5	871.3	878.8	NA	855	NA	1131	NA	NA	945	NA

2.5kHz		CR	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**	**2**	**2.1**	**2.2**	**2.3**	**2.4**	**2.5**	**2.6**	**2.7**	**2.8**	**2.9**	**3**
	S	AT	10	10	10	15	20	25	25	30	25	30	25	NA	25	NA	25	NA	25	NA	25	NA
		RT	160	130	70	75	75	75	75	75	75	80	80	NA	85	NA	80	NA	85	NA	85	NA
	L	AT	10	10	15	15	30	30	35	35	35	35	35	NA	30	NA	30	NA	30	NA	35	NA
		RT	350	535	640	655	760	775	780	785	815	770	795	NA	815	NA	820	NA	765	NA	720	NA

3kHz		CR	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**	**2**	**2.1**	**2.2**	**2.3**	**2.4**	**2.5**	**2.6**	**2.7**	**2.8**	**2.9**	**3**
	S	AT	10	10	12.5	22.5	27.5	30	35	35	37.5	NA	35	32.5	NA	32.5	32.5	NA	NA	32.5	NA	32.5
		RT	137.5	77.5	65	75	72.5	87.5	80	82.5	82.5	NA	87.5	92.5	NA	90	92.5	NA	NA	92.5	NA	100
	L	AT	10	10	12.5	25	32.5	32.5	37.5	42.5	40	NA	40	40	NA	40	42.5	NA	NA	42.5	NA	40
		RT	332.5	447.5	572.5	670	777.5	762.5	770	997.5	942.5	NA	942.5	987.5	NA	1048	945	NA	NA	1023	NA	807.5

3.5kHz		CR	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**	**2**	**2.1**	**2.2**	**2.3**	**2.4**	**2.5**	**2.6**	**2.7**	**2.8**	**2.9**	**3**
	S	AT	10	15	20	25	25	25	25	30	25	25	NA	25	20	NA	20	NA	20	NA	15	NA
		RT	40	40	50	50	60	60	60	60	60	50	NA	60	50	NA	55	NA	60	NA	50	NA
	L	AT	10	20	25	30	30	30	25	30	30	25	NA	25	25	NA	25	NA	25	NA	25	NA
		RT	160	305	330	360	530	365	460	265	290	330	NA	315	225	NA	340	NA	165	NA	15	NA

4kHz		CR	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**	**2**	**2.1**	**2.2**	**2.3**	**2.4**	**2.5**	**2.6**	**2.7**	**2.8**	**2.9**	**3**
	S	AT	8.12	21.25	27.5	30	26.25	25	26.88	28.75	29.38	33.75	25.62	NA	28.12	25.62	NA	26.88	NA	28.12	NA	NA
		RT	27.5	48.75	56.25	66.25	85.62	98.75	86.25	86.25	85.62	93.12	101.9	NA	93.75	125.6	NA	101.9	NA	80	NA	NA
	L	AT	11.88	18.75	26.88	28.75	36.88	38.12	34.38	37.5	32.5	33.12	33.75	NA	32.5	33.12	NA	35.62	NA	34.38	NA	NA
		RT	8.75	132.5	633.8	810.6	1034	1088	1197	1678	1304	1688	1889	NA	1925	1921	NA	1973	NA	1941	NA	NA

4.5kHz		CR	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**	**2**	**2.1**	**2.2**	**2.3**	**2.4**	**2.5**	**2.6**	**2.7**	**2.8**	**2.9**	**3**
	S	AT	10	15	20	25	30	25	25	25	30	30	25	30	NA	25	NA	25	NA	30	NA	25
		RT	35	35	40	45	50	70	55	70	40	60	50	70	NA	60	NA	55	NA	60	NA	30
	L	AT	15	20	25	30	30	35	35	35	35	35	30	35	NA	35	NA	25	NA	30	NA	30
		RT	90	450	300	690	470	760	835	510	1000	610	1230	875	NA	1465	NA	1855	NA	1805	NA	1710

5kHz		CR	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**	**2**	**2.1**	**2.2**	**2.3**	**2.4**	**2.5**	**2.6**	**2.7**	**2.8**	**2.9**	**3**
	S	AT	7.5	17.5	22.5	27.5	30	25	30	32.5	35	30	NA	30	30	25	NA	30	NA	27.5	NA	NA
		RT	10	37.5	47.5	47.5	52.5	52.5	55	67.5	55	67.5	NA	52.5	62.5	67.5	NA	62.5	NA	85	NA	NA
	L	AT	5	20	25	32.5	35	30	30	32.5	32.5	32.5	NA	37.5	30	32.5	NA	32.5	NA	32.5	NA	NA
		RT	10	10	217.5	242.5	770	830	905	920	795	1870	NA	1920	1188	1465	NA	1868	NA	1950	NA	NA

6kHz		CR	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3
	S	AT	8.75	15	27.5	22.5	30	30	23.75	27.5	25	27.5	27.5	NA	22.5	26.25	NA	25	NA	28.75	NA	27.5
		RT	12.5	12.5	466.3	1986	1933	1995	1946	1995	1995	1996	1959	NA	1995	1994	NA	1991	NA	1956	NA	1980
	L	AT	12.5	23.75	28.75	36.25	33.75	31.25	35	32.5	33.75	35	32.5	NA	30	35	NA	30	NA	28.75	NA	27.5
		RT	37.5	1483	1895	1906	1998	1986	1991	1991	1989	1984	1995	NA	1998	1990	NA	1998	NA	1998	NA	1985

(2) Flat loss CT: compression threshold; CR: compression ratio; S: short RT; L: long RT; AT: attack time; RT: release time

Hearing loss	250Hz	500Hz	1kHz	2kHz	4kHz	8kHz
	45	50	50	55	50	60

	200Hz	500Hz	1kHz	1.5kHz	2kHz	2.5kHz	3kHz	3.5kHz	4kHz	4.5kHz	5kHz	6kHz
CT	43	46	37	32	29	26	24	23	22	21	19	18

200Hz		CR	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3
	S	AT	37.5	215	268	215	310	592.5	755	NA	775	805	NA	925	NA	NA	825	NA	845	NA	NA	NA
		RT	560	720	220	510	1288	1070	567.5	NA	835	1072	NA	720	NA	NA	890	NA	970	NA	NA	NA
	L	AT	570	815	640	685	655	760	315	NA	972.5	790	NA	780	NA	NA	805	NA	785	NA	NA	NA
		RT	1825	1432	1995	1255	1358	1945	1865	NA	1383	682.5	NA	1920	NA	NA	1183	NA	1645	NA	NA	NA

500Hz		CR	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3
	S	AT	10	15	25	35	35	40	40	50	NA	55	NA	65	NA	NA	60	NA	NA	80	NA	NA
		RT	15	15	40	15	45	70	75	65	NA	45	NA	60	NA	NA	70	NA	NA	75	NA	NA
	L	AT	10	10	15	20	30	35	40	45	NA	50	NA	55	NA	NA	65	NA	NA	65	NA	NA
		RT	170	320	545	575	690	715	760	715	NA	805	NA	755	NA	NA	1135	NA	NA	1090	NA	NA

1kHz		CR	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3
	S	AT	10	10	10	17.5	15	27.5	25	32.5	NA	30	37.5	NA	42.5	NA	NA	42.5	NA	45	NA	NA
		RT	95	77.5	85	65	87.5	90	95	92.5	NA	102.5	95	NA	90	NA	NA	100	NA	105	NA	NA
	L	AT	10	10	10	12.5	25	30	35	37.5	NA	45	52.5	NA	50	NA	NA	55	NA	47.5	NA	NA
		RT	340	477.5	647.5	698	810	1005	877.5	982.5	NA	1048	1250	NA	1033	NA	NA	1188	NA	1208	NA	NA

1.5kHz		CR	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3
	S	AT	10	10	15	25	30	35	40	45	55	NA	70	NA	95	170	NA	NA	220	NA	245	NA
		RT	55	60	60	60	75	80	75	85	85	NA	95	NA	95	95	NA	NA	90	NA	95	NA
	L	AT	10	10	20	30	35	40	50	55	65	NA	80	NA	100	170	NA	NA	235	NA	275	NA
		RT	275	425	550	580	720	775	800	850	910	NA	925	NA	895	970	NA	NA	990	NA	990	NA

2kHz		CR	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3
	S	AT	10	10	11.25	17.5	22.5	25	32.5	32.5	NA	31.25	31.25	31.25	NA	33.75	NA	31.25	NA	NA	31.25	NA
		RT	81.3	68.75	73.75	78.8	86.25	71.25	78.75	87.5	NA	82.5	85	92.5	NA	97.5	NA	95	NA	NA	105	NA
	L	AT	10	10	12.5	15	27.5	31.25	32.5	36.25	NA	35	33.75	33.75	NA	36.25	NA	32.5	NA	NA	33.75	NA
		RT	489	485	697.5	690	798.8	985	925	968.8	NA	792.5	931.3	997.5	NA	1108	NA	1096	NA	NA	1288	NA

2.5kHz		CR	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3
	S	AT	10	10	10	85	85	20	20	25	25	30	30	NA	35	NA	30	NA	35	NA	30	NA
		RT	150	135	90	90	85	80	80	80	85	90	80	NA	90	NA	85	NA	85	NA	90	NA
	L	AT	10	15	10	10	20	20	25	30	30	35	35	NA	35	NA	40	NA	40	NA	35	NA
		RT	390	625	735	800	820	830	860	880	930	940	930	NA	920	NA	940	NA	945	NA	890	NA

3kHz		**CR**	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**	**2**	**2.1**	**2.2**	**2.3**	**2.4**	**2.5**	**2.6**	**2.7**	**2.8**	**2.9**	**3**
	S	AT	10	10	160	120	15	17.5	22.5	32.5	30	NA	35	37.5	NA	35	37.5	NA	NA	42.5	NA	40
		RT	155	107.5	92.5	90	82.5	82.5	92.5	87.5	92.5	NA	100	92.5	NA	90	95	NA	NA	97.5	NA	95
	L	AT	10	10	10	67.5	12.5	20	25	37.5	37.5	NA	40	45	NA	45	47.5	NA	NA	45	NA	52.5
		RT	240	470	650	800	817.5	820	960	962.5	957.5	NA	952.5	962.5	NA	1085	1033	NA	NA	1038	NA	1108

3.5kHz		**CR**	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**	**2**	**2.1**	**2.2**	**2.3**	**2.4**	**2.5**	**2.6**	**2.7**	**2.8**	**2.9**	**3**
	S	AT	10	10	10	10	15	20	20	25	25	25	NA	25	25	NA	55	NA	30	NA	25	NA
		RT	140	120	85	75	70	70	75	70	65	70	NA	75	70	NA	70	NA	85	NA	70	NA
	L	AT	10	10	10	10	15	25	25	30	30	30	NA	25	25	NA	70	NA	45	NA	65	NA
		RT	375	480	630	700	760	675	785	725	565	730	NA	600	685	NA	855	NA	370	NA	630	NA

4kHz		**CR**	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**	**2**	**2.1**	**2.2**	**2.3**	**2.4**	**2.5**	**2.6**	**2.7**	**2.8**	**2.9**	**3**
	S	AT	10.6	83.75	69.38	17.5	23.12	26.88	32.5	35	35	37.5	35	NA	36.88	36.25	NA	33.75	NA	34.38	NA	NA
		RT	117	90	80.62	72.5	93.75	81.25	86.25	86.88	88.75	83.12	93.75	NA	91.88	81.88	NA	81.88	NA	97.5	NA	NA
	L	AT	10	10.62	95.62	13.8	26.88	32.5	37.5	34.38	38.75	38.12	41.88	NA	43.12	39.38	NA	43.12	NA	38.75	NA	NA
		RT	490	608.1	760	948	1086	1076	1188	1303	1507	1086	1498	NA	1184	1504	NA	1876	NA	1893	NA	NA

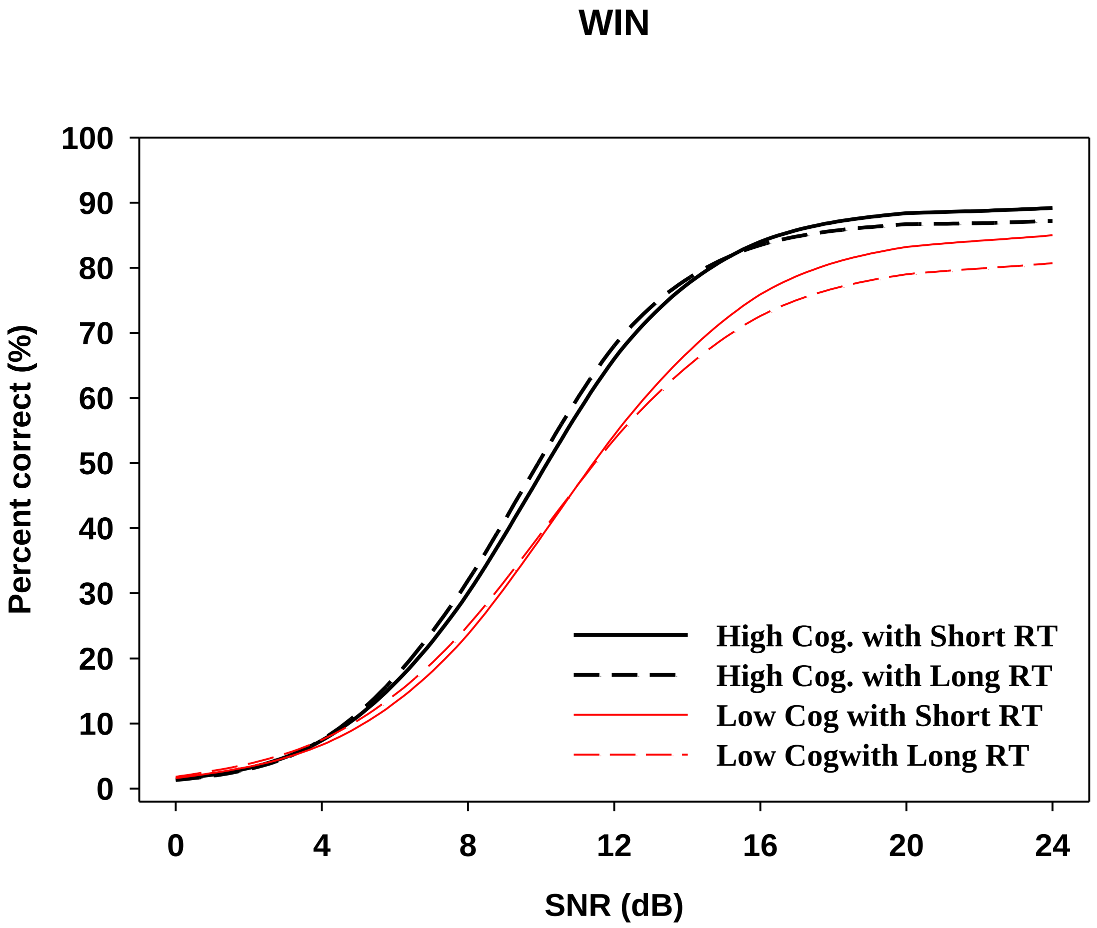
4.5kHz		**CR**	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**	**2**	**2.1**	**2.2**	**2.3**	**2.4**	**2.5**	**2.6**	**2.7**	**2.8**	**2.9**	**3**
	S	AT	10	10	15	25	25	30	30	30	30	30	30	30	NA	30	NA	25	NA	30	NA	25
		RT	50	50	45	50	50	60	70	55	65	50	50	55	NA	70	NA	55	NA	70	NA	40
	L	AT	10	10	20	30	35	35	30	35	35	35	30	30	NA	35	NA	30	NA	25	NA	25
		RT	280	225	340	450	360	710	275	360	470	840	950	985	NA	590	NA	360	NA	655	NA	915

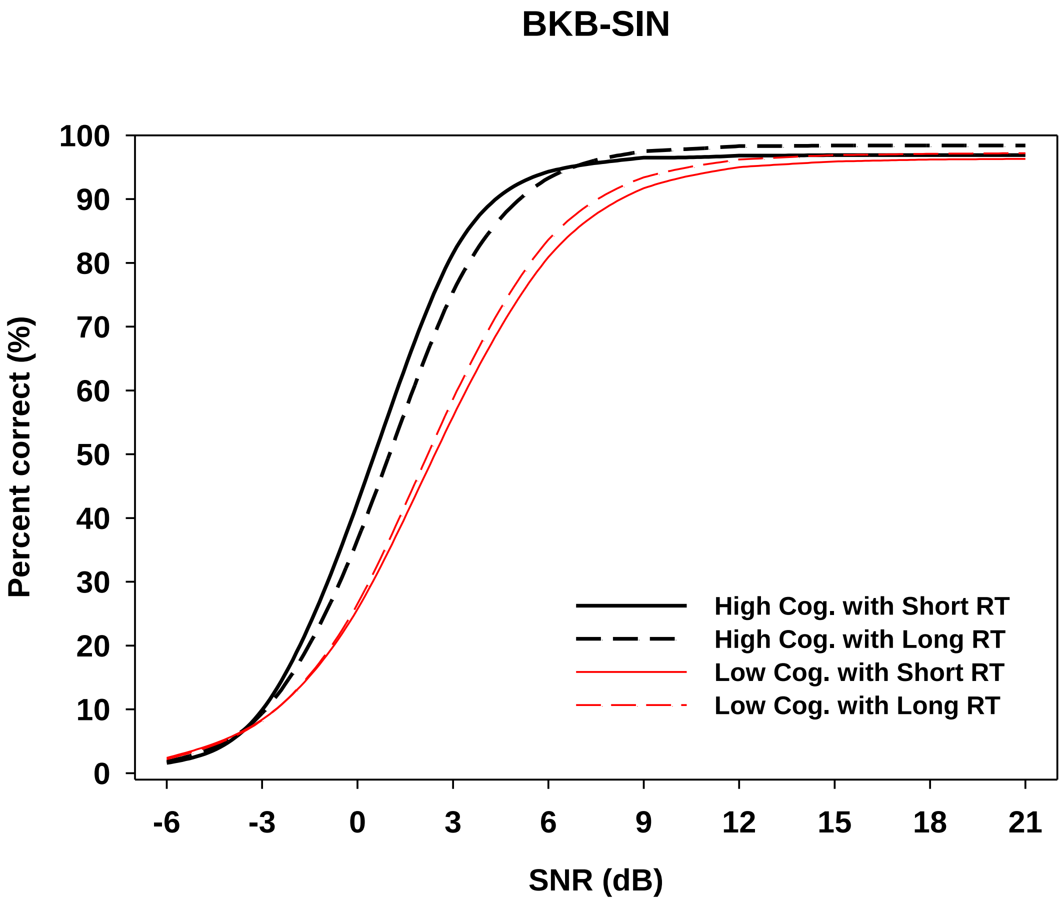
		CR	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**	**2**	**2.1**	**2.2**	**2.3**	**2.4**	**2.5**	**2.6**	**2.7**	**2.8**	**2.9**	**3**
5kHz	S	AT	5	17.5	25	25	25	25	32.5	30	32.5	35	NA	30	35	35	NA	30	NA	27.5	NA	NA
		RT	10	40	50	60	67.5	62.5	67.5	62.5	72.5	75	NA	75	72.5	82.5	NA	77.5	NA	82.5	NA	NA
	L	AT	7.5	20	25	27.5	32.5	35	35	32.5	37.5	32.5	NA	32.5	30	35	NA	30	NA	30	NA	NA
		RT	10	10	192.5	543	697.5	657.5	632.5	1208	622.5	820	NA	462.5	500	760	NA	607.5	NA	1625	NA	NA

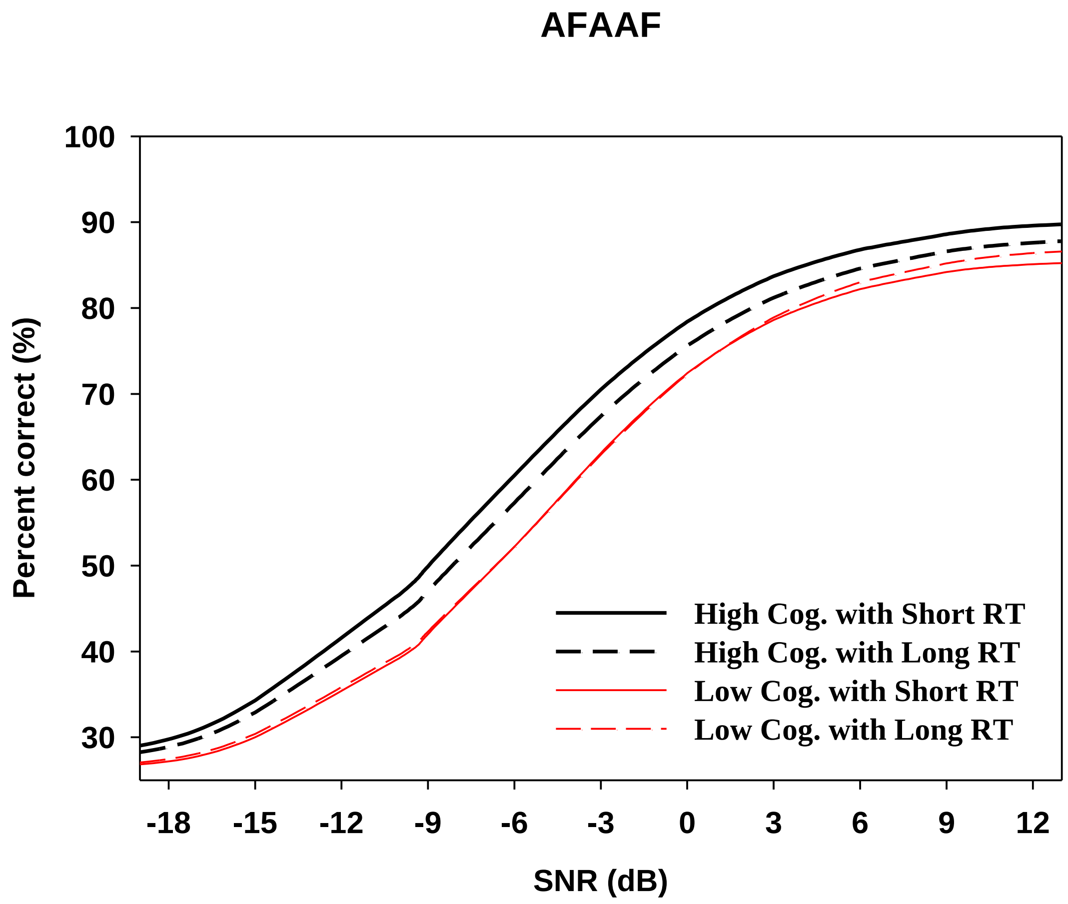
		CR	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**	**2**	**2.1**	**2.2**	**2.3**	**2.4**	**2.5**	**2.6**	**2.7**	**2.8**	**2.9**	**3**
6kHz	S	AT	8.75	17.5	26.25	25	27.5	28.75	23.75	23.75	25	25	27.5	NA	27.5	30	NA	28.75	NA	16.25	NA	20
		RT	11.3	11.25	12.5	28.8	58.75	1145	1646	1856	1921	1986	1985	NA	1665	1889	NA	1990	NA	1989	NA	1963
	L	AT	8.75	22.5	27.5	28.8	31.25	35	36.25	36.25	31.25	35	25	NA	30	27.5	NA	27.5	NA	23.75	NA	27.5
		RT	11.3	12.5	261.3	1055	1050	1995	1965	1963	1995	1996	1965	NA	1996	1973	NA	1979	NA	1989	NA	1996

Appendix B: Mean Psychometric Functions for Each Speech Recognition Test

Mean percent correct scores were obtained at each SNR. There were 16 participants in the cognitively low performance group and 13 participants in the cognitively high performance group. Psychometric functions for each cognitive group were fit to the mean data. Curves are shown for each combination of cognitive function and release time.




BKB-SIN
Percent correct (%)
100
90
80
70
60
50
40
30
20
10
0
-6
-3
0
3
6
9
12
15
18
21
SNR (dB)
High Cog. with Short RT
High Cog. with Long RT
Low Cog. with Short RT
Low Cog. with Long RT



* Tested SNRs were from -9 to +12 dB