THE EFFECT OF INDIVIDUAL VARIABILITY ON LISTENING EFFORT IN UNAIDED AND AIDED CONDITIONS

By

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CHAPTER I

INTRODUCTION

People with hearing loss have significant difficulty understanding conversations in many listening situations, especially when background noise is present (Hygge, et al., 1992; Stephens, et al., 1990; Tyler, Baker, & Armstrong-Bednall, 1983). This difficulty occurs, in part, because hearing loss impairs speech recognition, particularly in noise (Bacon, Opie, & Montoya, 1998; Chung & Mack, 1979; Festen & Plomp, 1990; Plomp, 1986). In addition to impaired speech recognition, hearing loss also increases listening effort, as measured by poorer recall on memory tasks (e.g. McCoy, et al., 2005; Rabbitt, 1991) and slower reaction times during dual tasks (e.g., Hicks & Tharpe, 2002). Listening effort is often conceptualized as the cognitive resources allocated for speech recognition (e.g. Fraser, et al., 2010; Hicks & Tharpe, 2002). As cognitive demands increase, so too does listening effort. Because cognitive capacity is limited (Kahneman, 1973), increased demands means fewer resources are available for other cognitive tasks like rehearsal, recall, environmental monitoring, or following conversation (Kahneman, 1973; Kantowitz, 1974; Moray, 1967).

The Ease of Language Understanding (ELU) model (Rönnberg, 2003; Ronnberg, et al., 2008) provides a conceptual framework for language understanding and includes explanations for increased listening effort due to background noise (Heinrich, Schneider, & Craik, 2008; Murphy, et al., 2000; Rabbitt, 1968) or hearing loss (McCoy, et al., 2005; Rabbitt, 1991). The model, displayed in Figure 1, suggests that language serves as the input to a buffer system, which rapidly and automatically binds phonological, semantic, syntactic and prosodic information.

This bound information is then compared to long-term memory stores. If the language information matches information in long-term memory, the listener has successfully perceived the language input. Conversely, if there is a mismatch between the perceived language units and long-term memory, a listener must exert explicit processing to achieve understanding. In other words, working memory resources must be allocated to successfully perceive a message if the input is degraded in some way and consequently does not match information stored in long-term memory. Thus, within the context of the ELU model, listening effort is the increase in resources necessary to resolve ambiguity between the language input and long-term memory store of a listener.

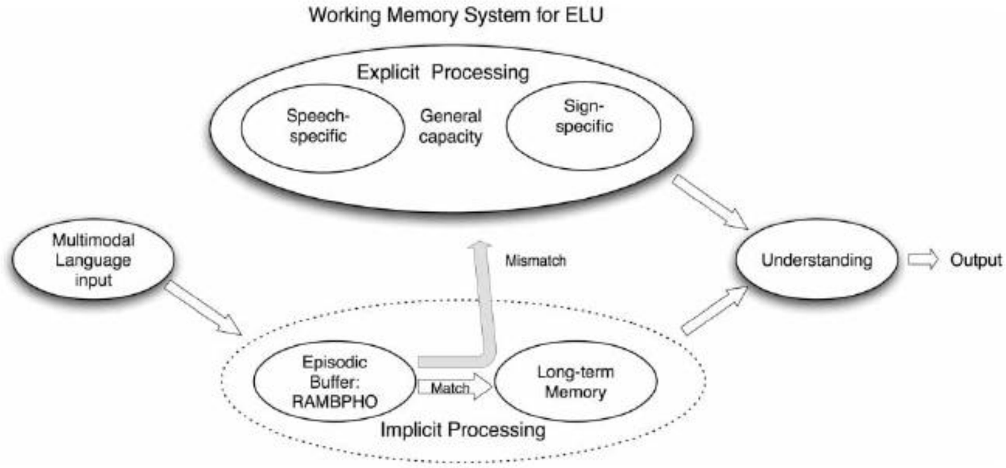

Figure 1. Working memory system for the Ease of Language Understanding model. (From Rönnberg et al., 2008).

Although the specific consequences of increased listening effort are less understood, intuitively, if cognitive resources are depleted, fewer resources are available for integrating information during a conversation. Listeners may have substantial difficulty remembering information presented earlier in a conversation or learning new information. In addition, over time, depleted cognitive resources may lead to increased mental fatigue. Indeed, people with hearing loss tend to take more personal days as a result of distress (Kramer, Kapteyn, & Houtgast, 2006) and increased need for recovery from work (Nachtegaal, et al., 2009).

Hearing Aids

Despite the detrimental effects of hearing loss on listening effort and the importance of improving listening effort with hearing aids, using hearing aids as a remediation for listening effort is not well documented. Despite documenting speech recognition improvements with hearing aids (e.g. Alcántara, et al., 2003; Hallgren, et al., 2005; Humes, et al., 2002; Larson, et al., 2002; Shanks, et al., 2002), relatively fewer investigations have focused on the effects of hearing aids on listening effort. Because increased listening effort may have significant negative long-term consequences (e.g., difficulty following conversation, decreased occupational productivity), it is important to determine if there are strategies or technologies that may ameliorate increased listening effort for people with hearing loss.

According to the ELU model, it is expected that any influences that impede accurate mental signal representation would increase listening effort. Whenever the language input results in a mismatch between input and long-term memory, listening effort will be increased. Conversely, when a signal can be easily matched with something in long-term memory, significantly fewer cognitive resources will be necessary and thus listening effort will be less. In the case of hearing loss, it has been suggested that listening effort is increased because the signal has been degraded by the loss and thus successful perception requires cognitive resources to derive an accurate mental representation (McCoy, et al., 2005; Pichora-Fuller, Schneider, & Daneman, 1995; Rabbitt, 1991). In addition to hearing loss, it has been shown that degrading the signal by introducing background noise also increases listening effort (e.g., Downs & Crum, 1978; Heinrich, et al., 2008; Larsby, et al., 2005; Murphy, et al., 2000; Rabbitt, 1968; Schneider, et al., 2000; Zekveld, Kramer, & Festen, 2010). Furthermore, Picou, Ricketts, and Hornsby (in press) found that, for some individuals, listening effort was reduced when signals could be better represented because visual information was available. Furthermore, in conditions with auditory-visual stimuli, listeners rated speech recognition as requiring less effort than auditory-only stimuli at the same SNR (Fraser, et al., 2010). Thus, those factors that degrade signal clarity and inhibit accurate mental representation (hearing loss, background noise, auditory-only stimuli) increase listening effort.

Some of these factors may be easier to remediate than others. Patients with hearing loss can be counseled to look at the talker of interest to use visual cues or to modify the environment whenever possible to reduce background noise. As there is no cure for sensorineural hearing loss, the only way to address the effects of the hearing loss is to fit a patient with hearing aids. However, the expected effect of hearing aids is unclear; they may obstruct or enhance signal clarity.

Under certain conditions, hearing aids may generate artifacts or distortions (Stone & Moore, 2004; Stone & Moore, 2008) or amplify previously inaudible background noise. These alterations to the target signal may require even further cognitive resources for successful perception because they further degrade signal clarity and cause a mismatch between input and long-term memories. Conversely, hearing aids improve audibility, which may result in improved speech recognition. Therefore, hearing aids may improve listening effort because, as speech recognition improves, listening effort decreases (Murphy, et al., 2000).

However, listening effort is not always tied to speech recognition; there are some conditions that alter listening effort without changing speech recognition (McCoy, et al., 2005; Pichora-Fuller, et al., 1995; Rabbitt, 1991; Surprenant, 1999). Thus, the potential improvements in listening effort from wearing hearing aids may extend beyond enhanced speech recognition. Even if hearing aids do not improve speech recognition, as may be the case in specific conditions with background noise (Gustafsson & Arlinger, 1994; Van Tasell, Larsen, & Fabry, 1988), hearing aids may still improve listening effort by increasing sensation level of the signal of interest. Previous researchers have found that reaction times and listening effort decrease when sensation level increases (Gatehouse & Gordon, 1990; Wright, Spanner, & Martin, 1981). Therefore, hearing aids may decrease listening effort by improving speech recognition and by increasing sensation level.

Indeed, several studies have shown that the impact of hearing aids on listening effort was beneficial, not detrimental (Downs, 1982; Gatehouse & Gordon, 1990). For example, Downs (1982) used a dual-task paradigm wherein listeners performed a monosyllable speech recognition task in noise simultaneously with a visual probe reaction time task. Results indicated that, on average, listeners were faster to respond to the probe light when listening through hearing aids, suggesting that hearing aids improved listening effort. However, not all studies have confirmed consistent hearing aid benefits for listening effort (Hallgren, et al., 2005; Nooraei, 2010). For example, Hallgren et al. (2005) found that hearing aids improved perceived listening effort, but not actual performance or reaction times for auditory and auditory-visual cognitive tasks in noise.

There are many possible reasons for the conflicting findings between studies that report a benefit of hearing aids for listening effort and those that do not. First, increases in background noise levels increase listening effort (Downs & Crum, 1978; Heinrich, et al., 2008; Murphy, et al., 2000; Rabbitt, 1968; Surprenant, 1999). It is possible that testing in conditions that are too easy (e.g., quiet, low level background noise) or conditions that are too difficult (high level background noise) may not be sensitive to changes in listening effort with hearing aids. Second, the choice of performance level appears to be important. Downs (1982) reported speech recognition performance levels of 50 and 70% in the unaided and aided conditions, respectively. Conversely, Hallgren et al. (2005) tested listeners with speech recognition performance at 100% both aided and unaided conditions. Indeed, listening effort benefit, as measured by reaction time, is bigger when speech recognition performance is between 15 and 85% compared to when performance is better than 85% (Gatehouse & Gordon, 1990). A third factor that may contribute to differences between studies may be hearing aid processing. There is evidence that some changes in hearing aid processing or technologies can further reduce listening effort (Baer, Moore, & Gatehouse, 1993; Sarampalis, et al., 2009). Some hearing aid technologies (e.g., noise reduction; Sarampalis, et al., 2009) change listening effort without changing speech recognition. If different studies used different hearing aid processing or enabled different hearing aid features, different patterns of results may be revealed.

Finally, an additional reason for discrepancies between studies may be due to the substantial inter-participant variability in hearing aid benefit of listening effort (Baer, et al., 1993; Downs, 1982). For example, Downs (1982) found that, on average, participants benefited from hearing aids on a dual-task paradigm as measured by increased reaction times to the secondary task. However, 9 of the 23 participants demonstrated slower reaction times in the aided condition. Therefore, the influence of hearing aids on listening effort may be different for different individuals. Although there are many possible variables that may contribute to variability in listening effort, one trait, working memory, stands out as a strong potential candidate as it is a central component of the ELU model (Rönnberg, 2003; Ronnberg, et al., 2008). Specifically, working memory resources become allocated when there is a mismatch between language input and long-term memory stores.

Working Memory Capacity

Working memory capacity is likely critical for speech recognition. Several researchers have reported that individual differences in capacity can account for variability in reading comprehension (Turner & Engle, 1989), the ability to ignore distracters (Conway, Cowan, & Bunting, 2001; Thompson, Garcia, & Malloy, 2007), speech recognition of time compressed speech (Cervera, et al., 2009), and speech recognition performance in noise (Lunner, 2003). In addition to being related to speech recognition performance, it has been suggested that working memory capacity can influence speech recognition performance with a hearing aid in noise (Foo, et al., 2007; Lunner & Sundewall-Thoren, 2007), hearing aid benefit (Davis, 2003), and success with fast-acting compression (Gatehouse, Naylor, & Elberling, 2003; Gatehouse, Naylor, & Elberling, 2006; Lunner & Sundewall-Thoren, 2007). Thus, it is possible that working memory capacity may be related to a listener’s susceptibility to the presence of noise in unaided and aided listening conditions.

Based on these findings, it is likely that working memory capacity impacts listening effort as well, although the effect of an individual’s capacity is unclear. While several different relationships are possible, it is hypothesized that listeners with smaller working memory capacities are more susceptible to the effects of background noise and hearing aids on listening effort. Specifically, similar to findings of speech recognition performance, listeners with smaller working memory capacities may experience increased listening effort in background noise and a greater decrease in listening effort from hearing aid use compared to those with larger capacities. Consider two listeners, one with limited and the other with ample cognitive resources. Then consider a change in the listening situation which affects listening effort, for example a decrease in available resources due to the addition of noise. This same decrease in the resource pool will be relatively large compared to the total pool of resources for the listener with limited cognitive resources in comparison to a listener with greater cognitive resources. In other words, changes in amplification and environment which affect listening effort (both positive and negative) will have a greater effect in listeners with more limited cognitive resources.

Examining the potential effects of working memory capacity on hearing aid benefit and susceptibility to noise is important because it could help explain differences between past studies, as well as have clinical implications for hearing aid patients. If predictive variables were identified that are related to hearing aid benefit, they could be used to guide hearing aid selection, fittings, and expectations counseling.

In order to be most clinically applicable, it is important to study listening effort in situations that are most realistic. One of the most realistic situations that is often ignored in the field of listening effort is the scenario where the listener can see the talker's face. Most of the research investigating listening effort has used auditory-only stimuli, while only a few have used auditory-visual stimuli. Thus, the impact of providing visual cues on listening effort is important, but is substantially less studied, especially for listeners with hearing loss.

Visual Cues

Regarding speech recognition, performance in auditory-visual (AV) conditions has been shown to be significantly better than performance in auditory-only (AO) conditions. The addition of visual cues improves speech recognition performance over a wide range of signal-to-noise ratios (SNRs; Erber, 1975; Grant, Walden, & Seitz, 1998; O'Neill, 1954; Sumby & Pollack, 1954), showing maximum AV benefits of 30-40% at intermediate SNRs (Ma, et al., 2009; Ross, et al., 2007). Regarding listening effort, there is some evidence that providing visual cues increases listening effort. For example, when noise was introduced during cognitive tasks (semantic and lexical decision making tasks), performance declined more in auditory-only than in auditory-visual conditions. However, reaction times increased more in the auditory-visual conditions. In other words, providing visual cues enhanced performance, but better performance came at the price of cognitive processing speed (Larsby, et al., 2005). Furthermore, when speech recognition performance was comparable in AO and AV conditions, Fraser et al. (2010) found that reaction times in a dual task were slower when visual cues were present, suggesting that integrating visual cues requires cognitive resources thereby increasing listening effort. Conversely, Picou, Ricketts, and Hornsby (in press) did not find a main effect of visual cues when speech recognition performance was matched in AO and AV conditions. Differences in task requirements (recall versus dual-task) and context (sentence versus single words) may account for some of the differences between the findings of Fraser et al. (2010) and Picou, Ricketts, and Hornsby (in press). However, differences in group data may obscure individual differences that may be predictable and it is likely that these inter-individual differences contributed to differences between studies. Picou, Ricketts, and Hornsby (in press) found that individuals with large working memory capacity were able to *benefit* from visual cues on a listening effort task in noise. In contrast, listeners with smaller working memory capacities were not impacted by visual cues. Therefore, it was hypothesized that individuals with smaller capacities will not be impacted by visual cues, but those with larger capacities can use visual cues to improve listening effort.

In addition to working memory capacity, an individual's skill level may also impact listening effort. For example, using synthetic speech stimuli, Francis and Nusbaum (2009) found that trained listeners responded faster than untrained listeners during a recall task. Because the synthetic speech stimuli were difficult to recognize, the authors concluded that training improves resource allocation and improves efficiency of working memory capacity.

Specific to the study of listening effort with visual cues, lipreading skill may influence individual variability because there is substantial inter-participant variability in lipreading ability in untrained listeners, especially in adverse listening conditions (Erber, 1969, 1975). For some listeners, lipreading may be easier or more automatic, and automatic processes are thought to require fewer cognitive resources (Hasher & Zacks, 1979). Perhaps listeners who have better lipreading ability rely on fewer cognitive resources to integrate audio and visual stimuli and may require less listening effort. Conversely, listeners for whom lipreading is more difficult will likely require more cognitive resources to integrate audio and visual stimuli in order to perceive a coherent message. Indeed, Picou, Ricketts, and Hornsby (in press), reported that listeners who are better lipreaders are more likely to make use of visual cues to reduce listening effort in noise. Together, these results suggest an individual's skills and experience with stimulus may impact listening effort.

In summary, people with hearing loss have difficulty following conversations, especially in noisy situations. Part of the difficulty comes from decreased speech recognition performance as a result of hearing loss, but the difficulty also comes from increased listening effort. Factors that increase listening effort are those that degrade the signal and thus require increased cognitive resources to achieve successful perception; these factors include background noise and hearing loss. Patients with hearing loss may be counseled to modify their environment by reducing background noise and they may be fitted with hearing aids. However, the effect of hearing aids on listening effort is unclear. Some studies have found hearing aid benefits, while others have not. Some of the reasons for discrepancies between studies may be that hearing aids improve listening effort in only some situations or that there are some individuals who can derive hearing aid benefit while others cannot.

Purpose

The purpose of the proposed study was to evaluate the possible benefit of hearing aids for reducing listening effort as measured in quiet and in noise. An additional purpose was to investigate the possible relationship between the magnitude of listening effort benefit and individual listeners' working memory capacity or lipreading skill. Listening effort was assessed objectively using a dual-task paradigm and subjectively using participants' ratings of listening effort. Identifying factors that may predict hearing aid benefit may help guide clinical practice for hearing aid selection and expectations counseling.

CHAPTER II

METHODS

Participants

Thirty-six adult adults aged 37 to 80 ($x = 64.9$, $\sigma = 9.5$) participated in this study; 21 of the participants were male. All participants had bilateral, sensorineural hearing loss as defined by interaural asymmetries < 15 dB at any two consecutive frequencies, normal tympanograms, and no air-bone gaps > 15 dB. See Figure 2 for average pure-tone, air-conduction audiometric thresholds for study participants. Twenty-seven participants were experienced hearing aid users ($x = 4.3$ years experience, $\sigma = 3.9$). All participants were native English speakers and had neither history of, nor any active, neurologic or otologic disease. Participants had binocular vision, corrected if necessary, of at least 20/40 as measured using a Snellen chart (Hetherington, 1954).

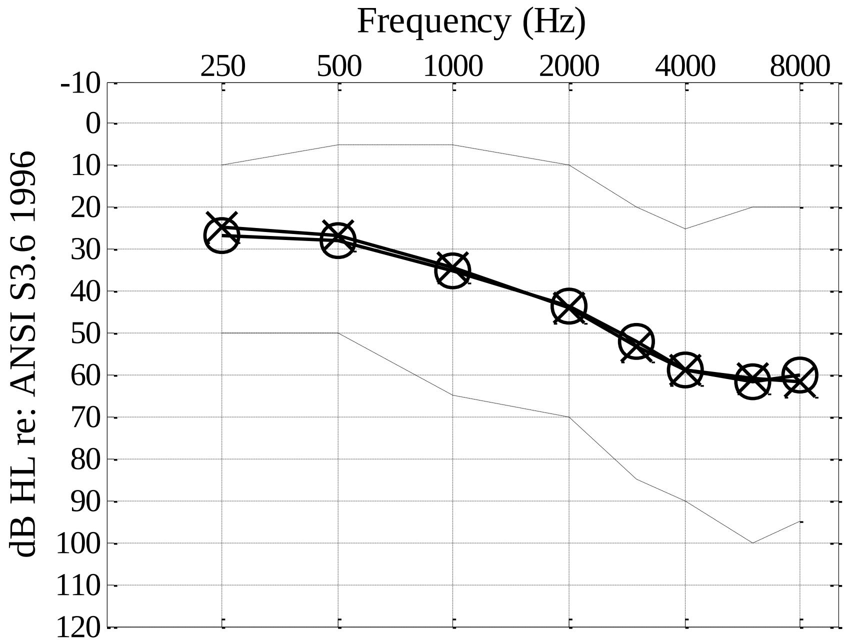

Figure 2. Mean air-conduction, pure-tone audiometric data for all study participants. Open circles indicate data for the right ear and Xs indicate data for the left ear. Dashed lines represent the minimum and maximum thresholds for all participants as a function of frequency.

Hearing Aids

In order to examine how amplification affects listening effort and interacts with potential predictive variables, participants were evaluated with and without hearing aids. All of the hearing aid features (noise reduction, directional microphones, speech enhancement) were turned off to ensure the hearing aid is acting only as a personalized amplifier and to ensure any potential interactions between feature activation and listening effort. Digital feedback suppression was left on to ensure adequate gain was possible. While the purpose of the current study was to determine the benefit from amplification for listening effort, future studies may investigate effects of signal processing and hearing aid features and individual differences in benefit from these technologies. Participants were each fitted Phonak Savia 211behind-the-ear (BTE) hearing aids with non-custom, occluding eartips. Hearing aids were fitted using National Acoustic Laboratories'- Nonlinear 1 (NAL-NL1) prescriptive formula (Dillon, 1999) for a 65 dB input and verified using the AudioScan Verifit using a record speech sample (carrot passage). See Figure 3 for the mean prescriptive target and mean real ear aided response for all participants. Because the degree to which amplitude compression influences listening effort is not yet known, care was taken to ensure linear hearing aid fittings for all participants. Because there was an interest in the effects of clinically fitted hearing aids using typical prescriptive gain procedures, audibility was not consistent across participants, nor was the improvement in audibility due to hearing aids. This study was therefore intended to measure potential benefits for listening effort in ecologically valid conditions, as described below. It should be noted however, that unaided speech recognition ability was also measured so that each subject served as their own control.

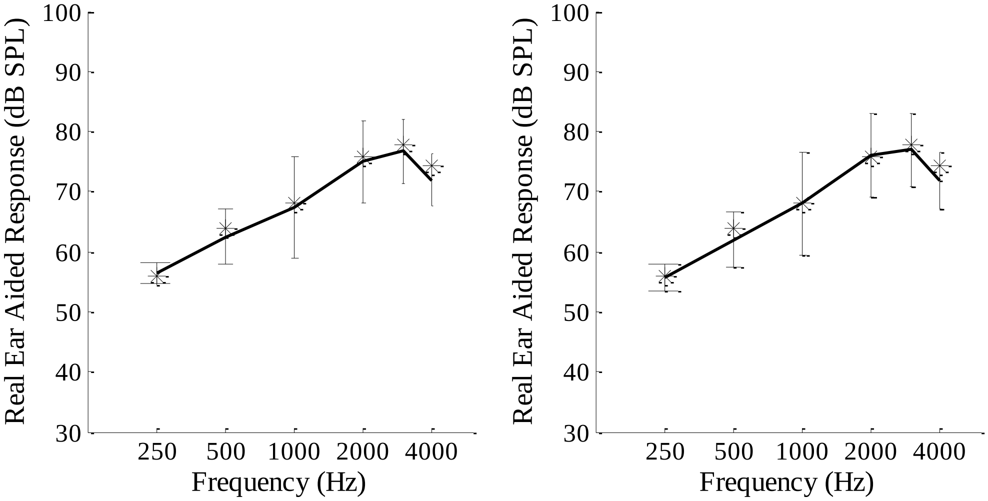

Figure 3. Mean NAL-NL1 prescriptive target and mean real ear aided response used to verify hearing aid settings prior to experimental testing. Symbols represent the mean prescriptive target and the line represents the mean real ear aided response. Error bars represent ±1 standard deviation of the real ear aided response.

Materials

To test listening effort, a dual-task paradigm was used. During this task, a listener performs a primary task (speech recognition) and a secondary task (visual reaction time task). A dual-task was chosen because previous investigations have shown similar tasks to be sensitive to the effects of hearing loss (Hicks & Tharpe, 2002) and hearing aid benefit (Downs, 1982). Furthermore, a recall task was not chosen because poorer general recall would be expected for older participants independent of hearing acuity (Anderson, Craik, & Naveh-Benjamin, 1999; Pichora-Fuller, et al., 1995; Tun, McCoy, & Wingfield, 2009), and participants were primarily elderly because hearing loss prevalence increases with advancing age (Corso, 1959; Cruickshanks, et al., 1998; Gates, et al., 1990). Furthermore, with a recall task, ceiling and floor effects might be expected and finding a performance level that allows for easy comparison between groups would have been difficult. Instead, despite likely age-related differences in reaction times (Anderson, 1999; Anderson, et al., 1999), the reaction time measure allowed for comparison of reaction times relative to an individual’s baseline and thus was likely less confounded by the effects of aging than a recall task.

Dual Task Paradigm: Speech Recognition Materials.

Speech stimuli consisted of monosyllabic words spoken by a female talker. The words are those in use by published or commercially available word lists, including words from the Central Institute for the Deaf (CID) W22 materials (Hirsh, et al., 1952), Northwestern University Auditory Test Number 6 (NU6), Phonetically Balanced Kindergarten Word Lists (PBK-50), and the Pediatric Speech Intelligibility Test (Jerger, et al., 1980). The recordings were digitized (sampling rate 41000 Hz, 29 frames per second) and edited to be single tokens each approximately 1700 ms in length and all have the same average root-mean-square (rms) value. The 480 recorded words were rank ordered by difficulty twice, once with AO presentation and once with AV presentation. This rank order information was used to create lists that are approximately equally difficult with AO and AV presentation modes, 8 lists of 60 words each in each presentation mode. During testing, the speech stimuli were presented at 65 dBA.

Background noise, when present, was a four-talker babble. The four talkers used to make the background noise were recorded individually using an omnidirectional microphone (EarthWorks) placed approximately 20 cm from the speaker's mouth in an anechoic chamber. Each speaker read passages from the Connected Speech Test (CST; Cox, Alexander, & Gilmore, 1987; Cox, et al., 1988). The CST is a speech recognition test that contains passages derived from a children's encyclopedia. The average rms level of each sentence was matched across all speakers and all sentences. Although sentences within a topic were kept together, the passage order was randomized for each talker such that no two talkers were reading the same passage at the same time in the final mix. The recordings for all talkers were mixed into a single channel of a wave file that was used for testing. During testing, the level of the background noise varied for each participant but ranged from 50 to 63 dBA ($x = 56$, $\sigma = 3.9$) in the AO conditions and from 50 to 68 dBA ($x = 63$, $\sigma = 3.8$) in the AV conditions. Thus, the SNR used for testing ranged from +15 to +2 dBA ($x = 9$, $\sigma = 3.9$) in the AO conditions and from +15 to -3 dBA ($x = +2$, $\sigma = 3.8$) in the AV conditions.

Dual Task Paradigm: Reaction Time.

The secondary task was a visual reaction time task. See Figure 4 for a schematic of a single trial of the dual task paradigm. During a trial, a rectangle was always presented immediately before a word was presented. The rectangle was either red (probe condition) or white (non-probe condition). The participants were instructed to press a red button on a keypad as quickly as possible whenever a red rectangle appeared, but not to press any button if the rectangle was white.

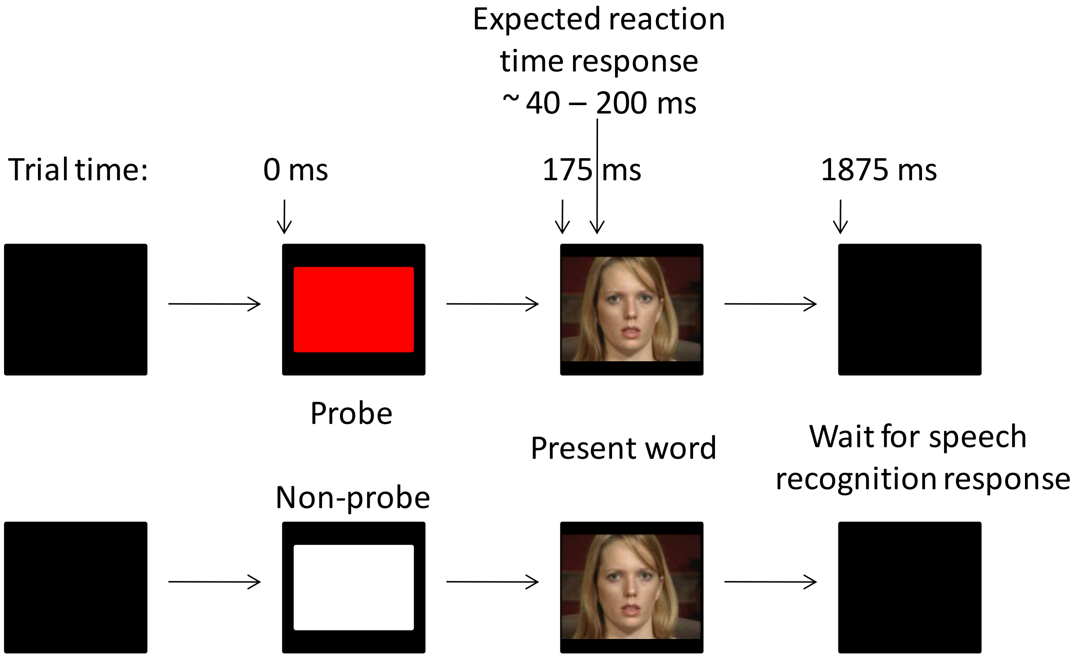

Figure 4. Dual-task paradigm schematic for probe (top panel) and non-probe (bottom panel) trials. In the auditory-visual conditions, the talker’s face is moving, while in the auditory-only conditions, the talker’s face is a still frame picture. In the probe condition, the box is red, while the box is white in the non-probe condition.

During each trial, the rectangle was visible for 125 ms and occurred 15 times during each 60 word list (see below for the conditions to be tested). Probe trial presentations were randomized within constraints that a probe occurred once during every block of four trials, but randomly within that block. Fifty milliseconds after the rectangle was turned off, the word file was started. The subject’s task was to repeat the word, regardless of whether a probe or non-probe trial was presented. After the participant repeated the word, the investigator pushed a button on another keyboard outside of the test booth to begin the next trial. Since this button push was not automated and the participants had varying reaction times, the time between each trial varied across presentations.

Subjective Ratings

In addition to the objective measure of listening effort (reaction time on the dual-task paradigm), a subjective measure of perceived effort was recorded for 33 of the 36 participants. Immediately after each condition (after a block of 60 trials is completed), participants were asked to rate how much “effort or concentration you had to put in to hear what was being said.” Participants were instructed to respond on an 11 point scale with endpoint anchors of 0 (no effort) to 10 (lots of effort). This is similar to a question from the Speech, Spatial and Qualities of hearing questionnaire (SSQ; Gatehouse & Noble, 2004).

Predictive Variables

In addition to the objective and subjective measures of listening effort, two predictive variables were measured: working memory capacity and lipreading ability. As described above, it was hypothesized that these predictive variables would be useful for explaining differences in listening effort between participants. Specifically, it was of interest to examine differences between individuals in hearing aid benefit. Because auditory working memory capacity measures can be influenced by hearing loss (Cervera, et al., 2009), a visual working memory capacity test, the Automated Operation Span Task (AOSPAN; Unsworth, et al., 2005) was used. The AOSPAN is a dual task paradigm designed to measure working memory capacity and has been shown to be correlated with higher level tasks like reading comprehension (Turner & Engle, 1989; Unsworth, et al., 2005). During the AOSPAN, participants are presented with an equation on a computer screen (e.g., (6+8)/2 = ?). The participant's task is to read and solve the equation. The participant is then presented with a possible solution on a new screen and asked to make a judgment about the correctness of the solution by using a mouse to click either "true" or "false" on the computer screen. After a choice is made, the participant is shown a letter which is to be committed to memory. Following presentation of a set of equation-letter pairs, a participant is asked to recall as many of the letters as possible. At time of recall, a 4 x 3 matrix of letters is presented to each participant, whose task is to select the letters presented in order, using the mouse. Following a practice session, set sizes vary from three to seven (three trials with each set size presented randomly). All equations include addition or subtraction inside a parenthetical, followed by multiplication or division. At the conclusion of the test, each participant received two scores: absolute score (total number of letters recalled from perfectly recalled sets), and a total score (number of letters recalled from all sets). For both scores, the total possible is 75.

In addition to working memory capacity, individual participant's lipreading skill was measured using the Revised Shortened Utley Sentence Lipreading Test (ReSULT; Updike, 1989). The ReSULT is a shorter version of the Utley Sentence Lipreading Test (Utley, 1946) and was designed to test lipreading ability quickly and reliably. The ReSULT contains two sets of 10 sentences spoken by female. Participants watch the speaker on a computer monitor but do not hear the speech. After each sentence, the participant's task is to repeat aloud what the speaker said. Participants earn one point for each word repeated correctly and do not receive credit for words repeated in the wrong order. Maximum possible scores are 43 and 46 on the first and second list, respectively. Participants were all tested using Form A first and Form B second. The sum of scores was taken as the measure of lipreading ability.

Test Environment

During testing, a participant was seated in the center of a sound attenuated booth. A 24" LCD video monitor placed on top of a loudspeaker (Tannoy System 6) was positioned 1.5m from the participant. All stimuli were presented via the same loudspeaker / monitor system. For recall testing and SNR setting, Presentation® software (Neurobehavioral Systems v. 14.2) installed on a PC outside the test booth delivered the monosyllabic tokens via custom programming. The audio output was routed to an audiometer (GSI 61) for level control and then to the loudspeaker. The background noise, if present, was delivered to the test loudspeaker from a DVD player (Panasonic DVD S54) via the other channel of the audiometer. For lipreading testing, the ReSULT was played a DVD player (Panasonic DVD S54) and delivered to the monitor inside the test booth. For working memory capacity testing, the AOPSAN task was administered via E-Prime using custom programming (Psychology Software Tools v. 2.0) from the computer outside the test booth. During the AOSPAN testing, the participant was given a mouse and was seated inside the test booth.

Procedures

During an initial evaluation, audiometric and vision testing was performed to ensure participant eligibility based on hearing status (pure-tone audiometric testing) and binocular visual acuity (Snellen chart). In addition, predictive variables were collected including: working memory capacity (AOSPAN) and lipreading ability (The ReSULT). Also during the initial visit, the SNR used for the dual-task paradigm was set individually for each participant and chosen to equate speech recognition performance in AO and AV unaided noise conditions to reduce the risk that any effects of visual cues, if present, would be due to differences in word recognition. In addition, setting the SNR ensured that each participant's unaided speech recognition performance in noise was in the 50-70% range that is likely to be most sensitive to changes in listening effort as discussed above.

To set the SNR for use during the dual-task, four AO and four AV lists composed of 60 words each were used. All 8 lists are approximately equally intelligible. At a given SNR, speech recognition of 60 words were tested. The SNR was then adjusted to closer approximate speech recognition performance in the target range and 60 more words were be tested. If performance was between near 50%, 120 more words were tested to confirm the performance level. Otherwise, the SNR was adjusted again and speech recognition of 60 more words will be tested. If necessary, the final 60 words were used to confirm appropriate SNR setting. The same procedure was completed with AO and AV stimuli. Care was taken to ensure that, for each participant, speech recognition performance was the same in AV and AO condition. In this manner, dual task will be completed at approximately the same speech recognition performance level for AO and AV stimuli in noise in the unaided condition.

The order of study procedures was the same across all participants during the initial visit. Specifically, the order was always: consent, hearing evaluation, vision screening, AOSPAN, ReSULT, and SNR setting. The order of study procedures was held constant so any fatigue effects are consistent across participants.

During a second visit on a subsequent day, participants completed the dual-task testing in eight conditions. These eight conditions varied by background noise (quiet, noise), visual cues (AO, AV), and hearing aids (unaided, aided). Specifically, the conditions were: 1) AO stimuli in quiet unaided, 2) AO stimuli in noise unaided, 3) AV stimuli in quiet unaided, 4) AV stimuli in noise aided, 5) AO stimuli in quiet aided, 6) AO stimuli in noise aided, 7) AV stimuli in quiet aided, and 8) AV stimuli in noise aided. Each of these conditions was tested twice. Conditions were blocked and counterbalanced across participants by presentation mode (AO, AV), by noise level (quiet, noise), and by hearing aid status (unaided, aided).

All participants completed a structured practice sequence before testing commenced. First, a participant was tested in AO quiet and then AV noise stimuli, but they were asked only to perform the reaction time portion of the test, not speech recognition during these first two trials. Next, a participant completed two practice conditions in background noise, performing both the speech recognition and reaction time tasks, first with AO stimuli and then with AV stimuli. The fifth and final practice condition was again a reaction-time-only task using AO stimuli in quiet. The results from this condition served as a baseline for reaction time performance.

Data Analysis

Prior to analysis, the data were transformed in the following manner. The total ReSULT (combination of Forms A and B) scores and total AOSPAN scores were transformed into normalized z-scores such that the new means and standard deviations were 0 and 1, respectively. These z-score transforms were completed based on the means and standard deviations collected in the current data set. In addition, the average speech recognition score over the two runs in each condition was converted to rationalized arcsine unit (rau) following the equations in Studebaker (1985). With regards to the reaction time measure, the median reaction time from the last 14 of 15 total probes in a condition was used. The participant’s baseline reaction time, as measured during the fifth practice condition, was then subtracted from the median reaction time in each condition. The purpose of this subtraction was to provide an indication of “listening effort” that was separate from a physical reaction time. The average reaction time of two runs (minus the baseline) in each condition was used for all analyses.

To analyze listening effort, an analysis of variance (ANOVA) was completed using the average median reaction time data as described above. The three within-subject variables were background noise (present, absent), visual cues (present, absent), and hearing aids (present, absent). In addition to the objective measure of listening effort (reaction time on the dual-task paradigm), subjective ratings were analyzed in the same manner. For both objective and subjective results, significant main effects and interactions were further explored using Tukey HSD post-hoc analyses. In addition to the objective and subjective measures of listening effort, it was of interest to analyze speech recognition performance in the same manner (three within subject variables). While not under direct hypothesis, these results are displayed alongside the indices of listening effort.

In addition to the general ANOVA, multiple regression analyses were conducted to evaluate the potential for each of the two predictive variables (lipreading ability, working memory capacity) to predict hearing aid benefit for objective listening effort. Furthermore, two additional multiple regression analyses were used to determine if benefit from visual cues or susceptibility to background noise is predictable based on individual variations in working memory capacity or lipreading ability.

CHAPTER III

RESULTS

Speech Recognition

Figure 5 displays the mean speech recognition performance in all eight conditions. The repeated-measures ANOVA with three within-subject variables (Hearing Aids, Visual Cues, Background Noise) revealed significant main effects of Hearing Aids ($F_{1,36} = 14.748$, $p < 0.001$), Visual Cues ($F_{1,36} = 81.981$, $p < 0.001$), and Background Noise ($F_{1,36} = 199.222$, $p < 0.001$). These results suggest that hearing aids and visual cues improved speech recognition performance, and background noise impaired performance. However, there were significant interactions between Hearing Aids x Visual Cues ($F_{1,36} = 5.099$, $p < 0.05$), Hearing Aid x Background Noise ($F_{1,36} = 8.127$, $p < 0.01$), and Visual Cues x Background Noise ($F_{1,36} = 90.691$, $p < 0.001$). These results indicate that the effects of hearing aids depended on test modality (AO, AV) and on the background noise (present, absent), and that the effect of visual cues depended on the background noise (present, absent).

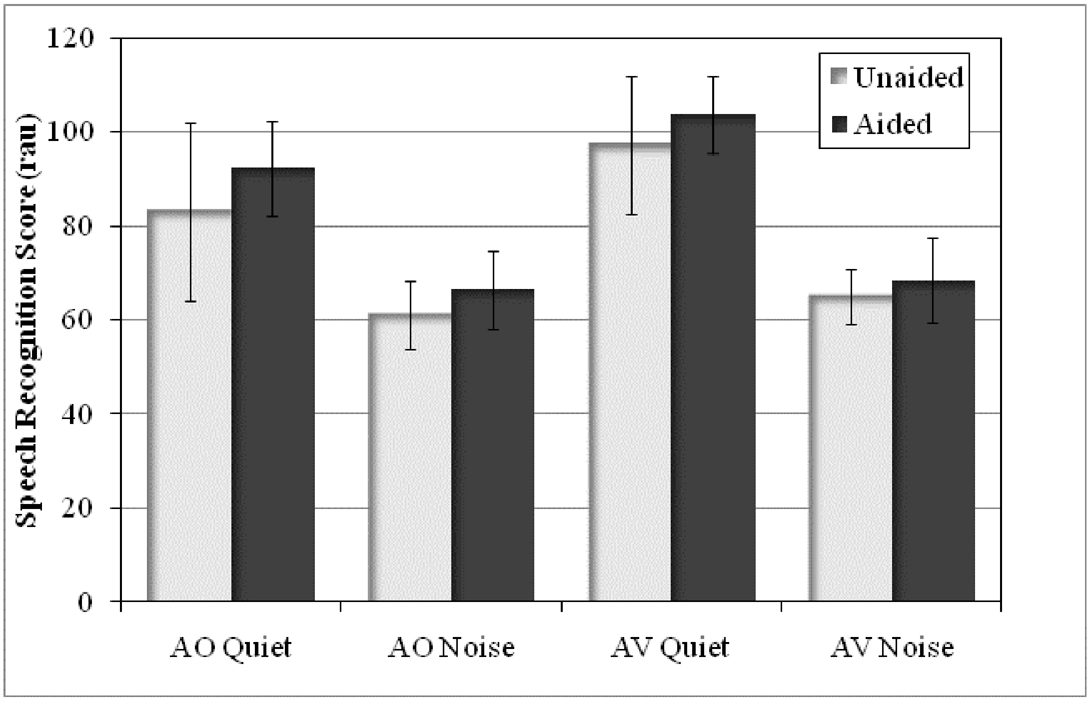

Figure 5. Mean speech recognition score for all participants in all eight test conditions. Light bars indicate unaided conditions and dark bars indicate aided conditions. Error bars represent ±1 standard deviation from the mean.

Regarding the Hearing Aid x Vision interaction, post-hoc Tukey HSD comparisons revealed that participants received hearing aid benefit in the auditory-only ($p < 0.001$) and auditory-visual ($p < 0.001$) conditions. However, there was no significant difference between the AV unaided condition and the AO aided condition. Furthermore, the hearing aid benefits were small in both modalities, 7.2 and 4.9 rau in the AO and AV conditions, respectively.

Regarding the Hearing Aid x Background Noise interaction, follow-up testing revealed that all comparisons were statistically significant ($p < 0.001$). In other words, there was significant hearing aid benefit in quiet and in noise, although the benefit was smaller in noise (4.4 rau) than in quiet (7.7 rau). Furthermore, there was a significant effect of background noise in both the aided and unaided conditions. This is an expected effect because the SNR for testing was chosen for each participant to ensure that background noise adversely impacted speech recognition performance.

Finally, regarding the Visual Cues x Background Noise interaction, follow-up testing revealed that all comparisons were statistically significant ($p < 0.001$). In other words, performance in quiet was better than performance in noise in the AO and AV conditions. However, the effect of noise was greater in the AV conditions than in the AO conditions, 33.8 and 23.9 rau, respectively. This effect is not surprising and is an artifact of experimental design. In quiet, no attempt was made to match speech recognition performance between AO and AV conditions. However, because visual cues improve speech recognition (e.g., Erber, 1975; O'Neill, 1954), performance was better in AV (100.4 rau) conditions than in AO conditions (87.7 rau) in quiet. Conversely, it was the aim of this study to test participants using background noise levels that yielded speech recognition performance between 50 and 70% in both AO and AV conditions for each participant. Because performance was so similar between AO and AV conditions in noise (63.8 and 66.8 rau, respectively), there was a significant an interaction between background noise and visual cues.

Objective Listening Effort

Median reaction times during dual-task testing provided an indication of objective listening effort. To reduce some of the variability associated with physical reaction time measures, a participant’s baseline reaction time was subtracted from the median reaction time in each condition. Figure 6 displays the mean reaction time (minus baseline) for all participants in the eight test conditions, averaged over the two runs in each condition. Correlation analysis revealed that the two runs across all participants and conditions were significantly correlated ($r^2 = 0.66$, $p < 0.001$). To analyze the main effects of interest, a repeated-measures ANOVA was completed. The repeated-measures ANOVA with three within subject variables (Hearing Aids, Visual Cues, Background Noise) revealed only a significant main effect of Background Noise ($F_{1,36} = 9.191$, $p < 0.01$). The main effects of Hearing Aids and Visual Cues were not significant and there were no significant interactions. While no significant hearing aid effect was present, there was a trend of slightly shorter reaction times when aided compared to unaided, particularly for the AO presentations. This trend did not reach statistical significance, however, because individual data indicated that some patients clearly demonstrated a hearing aid benefit for listening effort, while others demonstrated a hearing aid detriment. Specifically, the range of performance change from unaided to aided across all four conditions (AO quiet, AO noise, AV quiet, AV noise) was -99 ms (hearing aid detriment) to 153 ms (hearing aid benefit). Only approximately 8 to 20% of participants (depending on the condition) demonstrated hearing aid benefit of more than 40 ms. Taken together, these results suggest that neither hearing aids nor visual cues affected listening effort, but background noise significantly increased listening effort.

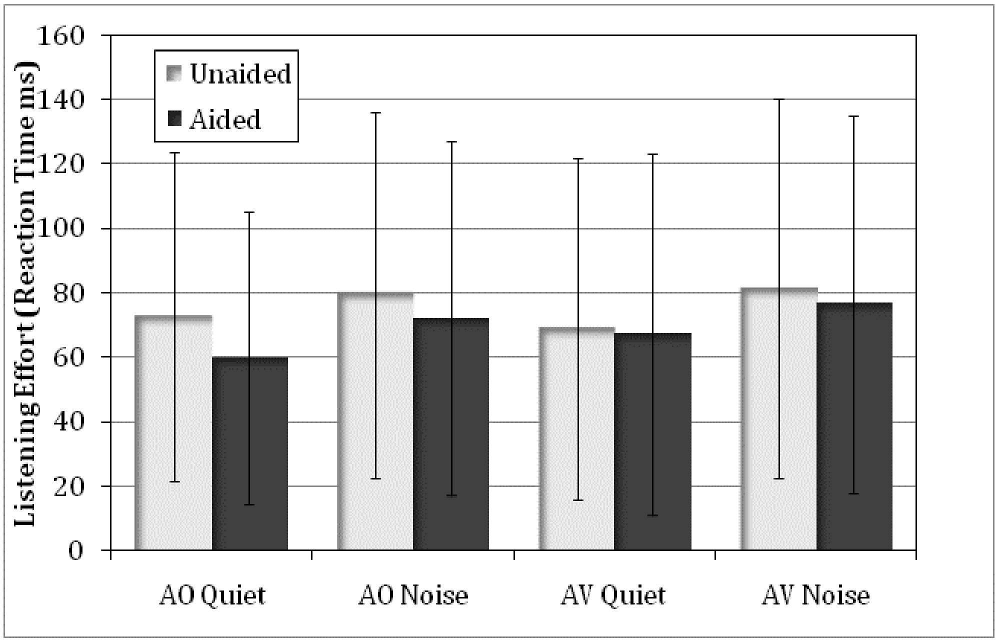

Figure 6. Mean reaction time (minus baseline) to the probe conditions during the dual-task in the eight test conditions. Light bars indicate unaided conditions and dark bars indicate aided conditions. Error bars represent ±1 standard deviation from the mean.

While there were no main effects of hearing aids or visual cues, it was of interest to determine if it was possible to predict which individuals were more likely to experience a change in listening effort with a change in hearing aids, visual cues, or background noise. To do this, three sets of reaction time data were calculated: hearing aid benefit scores (reaction time unaided – reaction time aided), vision benefit (reaction time AO – reaction time AV), and noise susceptibility (reaction time noise – reaction time quiet). For each data set, a multiple regression analysis was performed using two independent variables (ReSULT z-score and AOSPAN z-score).

With regards to hearing aid benefit, the only predictive variable that was statistically significant was lipreading ability in the AV quiet condition ($\beta = 0.374$, $t(33) = 2.207$, $p < 0.05$). In other words, in the AV quiet condition, participants who were better lipreaders were less likely to have hearing aid benefit for listening effort (see Figure 7). The predictive variables were not significantly related to hearing aid benefit in AO quiet, AO noise, or AV noise.

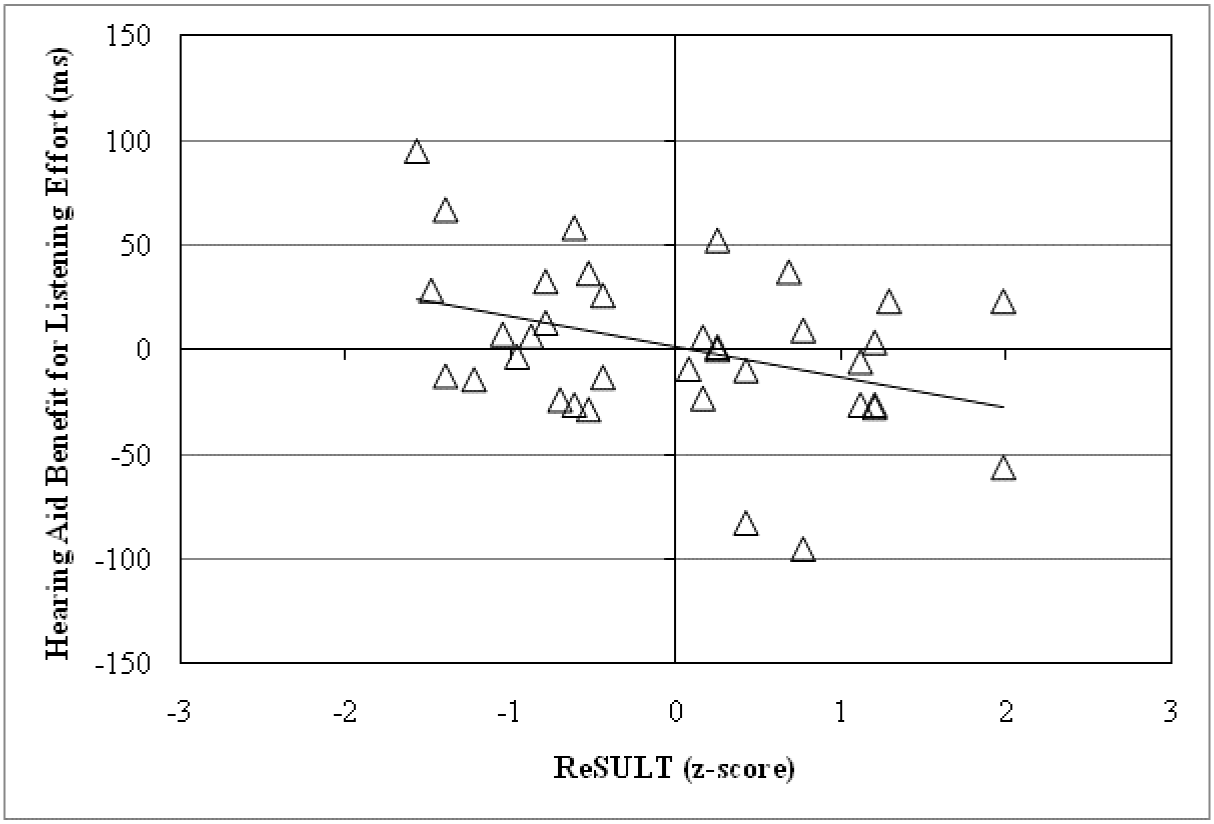

Figure 7. Relationship between lipreading ability and hearing aid benefit in auditory-visual condition with no background noise present. Benefit scores were calculated by subtracting the score in aided condition from the score in the unaided condition. Therefore, a positive benefit score indicates a faster reaction time and thus less listening effort.

With regards to benefit from visual cues, the only predictive variable that was statistically significant was lipreading in quiet in the unaided condition ($\beta = 0.479$, $t(33) = 3.007$, $p < 0.01$). In other words, participants who were better lipreaders were more likely to experience listening effort benefit from having visual cues available (see Figure 8). While there was a trend for lipreading ability to be related to benefit from visual cues in quiet in the aided condition, the effect was not significant (β = 0.316, t(33) = 1.835, *p* = 0.076). Neither working memory capacity nor lipreading ability was significantly related to benefit from visual cues in noise in either the quiet or noise aided conditions. With regards to susceptibility to background noise, neither of the predictive variables (working memory capacity and lipreading ability) were significant predictors in the AO unaided, AV unaided, AO aided, nor AV aided conditions.

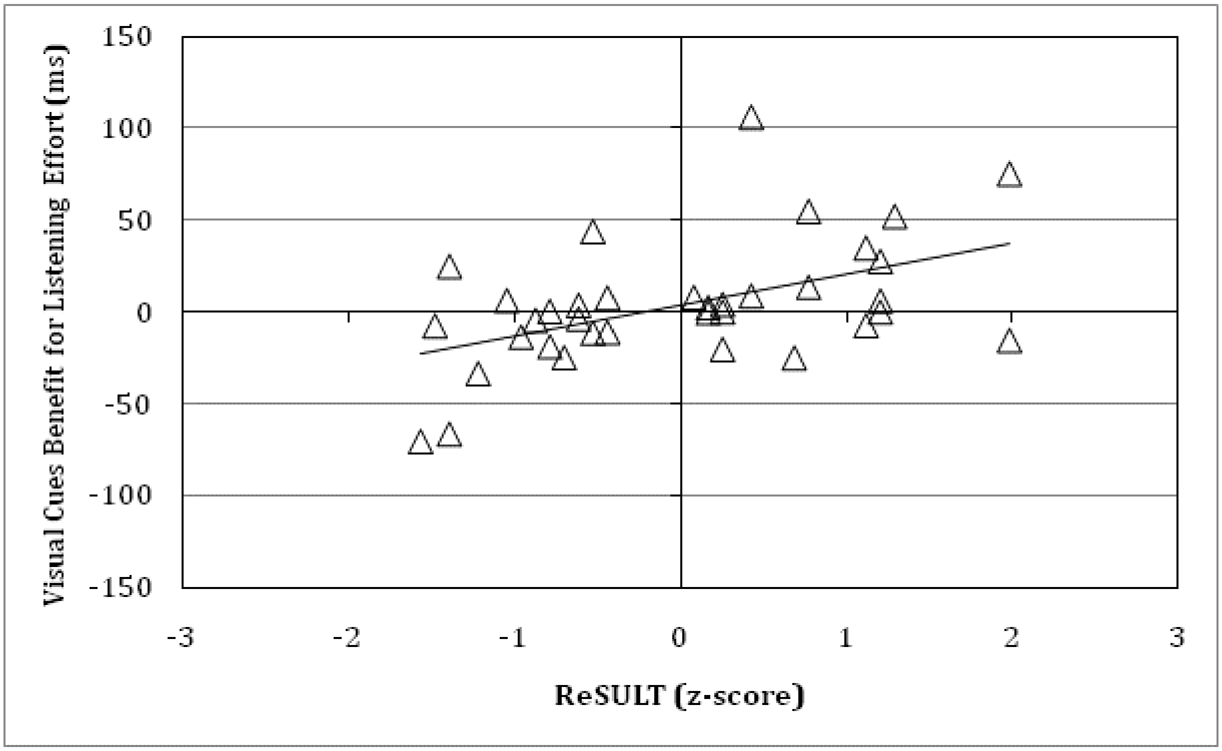

Figure 8. The relationship between lipreading ability and the effect of visual cues on listening effort in quiet. Benefit scores were calculated by subtracting the score in the auditory-visual condition from the score in the auditory-only condition. Therefore, a positive benefit score indicates a faster reaction time and thus less listening effort.

Subjective Listening Effort

In addition to the objective measure of listening effort (reaction time), participants were asked to rate their subjective impression of listening effort on a scale of 0 to 10 (higher number indicates more listening effort). See Figure 9 for the mean subjective ratings in all eight conditions. These subjective ratings were analyzed using repeated-measures ANOVA with three within-subject variables (Hearing Aids, Visual Cues, Background Noise). The results of the analysis revealed a main effect of Vision ($F_{1,32} = 8.838$, $p < 0.01$) and a main effect of Background Noise ($F_{1,32} = 156.091$, $p < 0.0001$). These results suggest that visual cues improved listening effort, but background noise increased listening effort. There were two significant interactions, Hearing Aids x Background Noise ($F_{1,32} = 25.46$, $p < 0.001$) and Visual Cues x Background Noise ($F_{1,32} = 46.223$, $p < 0.001$), suggesting that the effect of hearing aids and the effect of visual cues varied as a function of background noise.

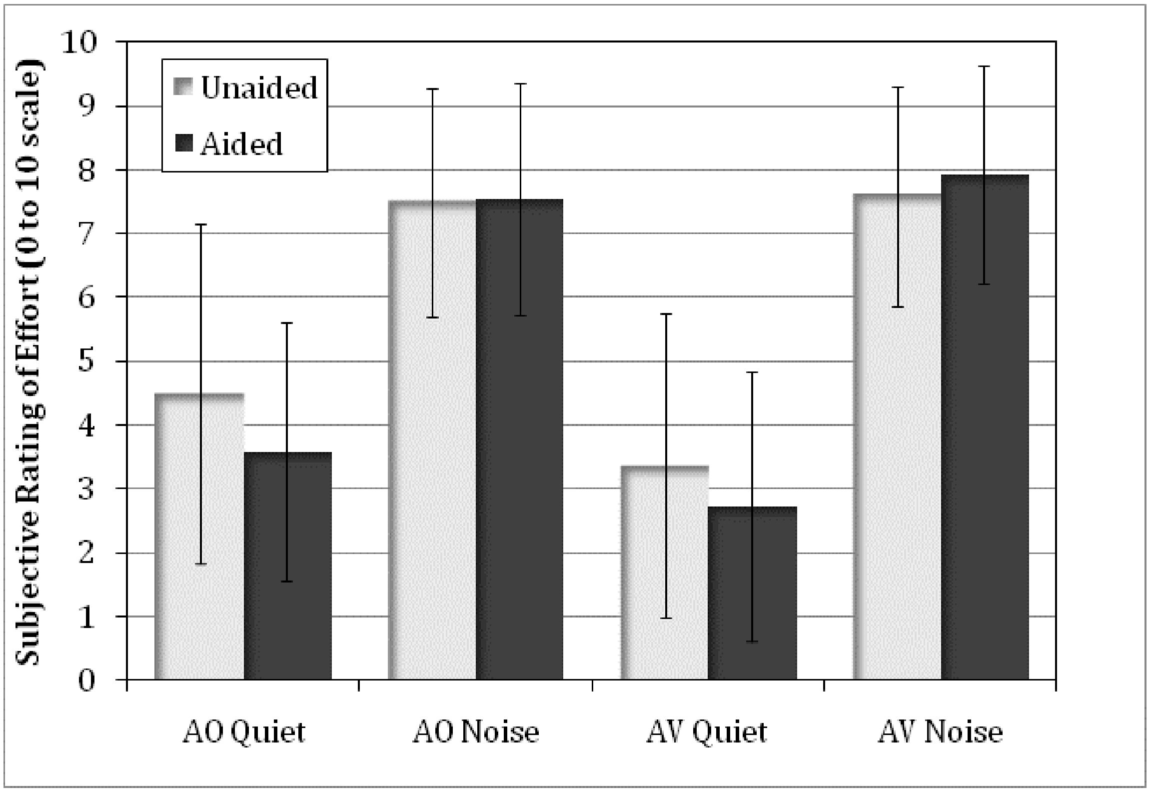

Figure 9. Mean subjective rating of listening effort following the dual-task testing in the eight test conditions. Ratings were on a scale of 0 to 10, where 10 indicates higher perceived listening effort. Light bars indicate unaided conditions and dark bars indicate aided conditions. Error bars represent ±1 standard deviation from the mean.

To further explore these significant interactions, Tukey HSD post-hoc comparisons were used. Analysis of the Hearing Aids x Background Noise interaction revealed that background noise increases subjective listening effort in the aided and unaided conditions ($p < 0.001$) and that hearing aids reduced subjective listening effort in quiet ($p < 0.001$), but not in noise. Analysis of the Visual Cue x Background Noise interaction revealed that background noise increased subjective listening effort in the AO and AV conditions ($p < 0.01$) and that visual cues reduced subjective listening effort in quiet ($p < 0.01$), but not in noise. Taken together, these results suggest that background noise increased subjective perception of listening effort, but visual cues and hearing aids reduced perceived effort. However, neither visual cues nor hearing aids reduced perceived listening effort in the presence of background noise.

To ensure that the ratings of perceived listening effort were measuring something similar to objective listening effort, correlation analyses were completed to examine the relationships between the subjective ratings (participant ratings) and objective measure of listening effort (reaction time), in addition to subjective ratings and speech recognition performance. To do this, correlations between subjective ratings and either speech recognition performance or reaction time were calculated for the aided or unaided conditions, collapsing across modality (AO, AV) and noise (present, absent). Correlations between subjective ratings and speech recognition scores were significant in the unaided ($r^2 = -0.750$, $p < 0.001$) and aided ($r^2 = -0.764$, $p < 0.001$) conditions, suggesting that as speech recognition performance improved, participants reported less subjective effort. Correlations between subjective ratings and objective measures listening effort were not significant. These results suggest that the subjective ratings of listening effort reflected individuals perceptions of speech recognition performance rather than objective listening effort as quantified by changes in reaction time (see Figure 10).

CHAPTER IV

DISCUSSION

Speech Recognition

Although the primary purpose of this study was to examine the effects of hearing aids, visual cues, and background noise on listening effort, it was also important to evaluate speech recognition to ensure the variables of interest had predictable effects on speech recognition. Indeed, the pattern of speech recognition performance was expected. By experimental design, background noise impaired speech recognition performance. Also by design, speech recognition performance in background noise was approximately the same in the auditory-only (AO) and auditory-visual (AV) conditions (see Figure 5).

With regards to hearing aid benefit, the current results suggest that participants received hearing aid benefit on the speech recognition task during AO and AV conditions, although the benefit was smaller in AV conditions. These results are consistent with past studies that have found objective speech recognition hearing aid benefit in AV conditions, although a trend towards less benefit than in AO conditions (e.g., Cox & Alexander, 1991; Haggard, Foster, & Iredale, 1981). Similarly, and consistent with the present results, previous studies have reported significant hearing aid benefit in quiet, but reduced hearing aid benefit in noise. Many previous investigators have found the most hearing aid benefit in favorable listening conditions when benefit is measured either objectively (e.g., Cox & Alexander, 1991; Duquesnoy & Plomp, 1983) or subjectively (e.g., Walden, Demorest, & Hepler, 1984).

Objective Listening Effort

Hearing Aids

Because hearing aids are a primary means of rehabilitation of sensorineural hearing loss, it was of considerable interest to investigate the potential effect of hearing aids on improving listening effort for people with hearing loss. However, there was no main effect of hearing aids on objective listening effort in the current study. These results are consistent with some previous findings that hearing aids do not influence listening effort (Hallgren, et al., 2005). However, Hallgren et al (2005) used reaction time measures in response to complex cognitive tasks as an indication of listening effort, while a dual-task paradigm was employed for the present study.

Other investigators who have used dual-tasks to measure listening effort have demonstrated benefits of hearing aid use on the reaction time measure. For example, Downs (1982) reported that reaction times were faster for participants when they were tested using hearing aids than when tested without hearing aids. As the methodologies between those reported by Downs and those employed in the present study were very similar (monosyllable speech recognition primary task and visual probe reaction time secondary task), one might expect similar results between the two studies.

Although there were minor differences in the methodologies, the largest differences between the present study and the one reported by Downs are the magnitude of the effect sizes. Downs reported average reaction times of 104 and 130 ms for aided and unaided conditions, respectively. Conversely, the average reaction times in the current study were 69 and 76 ms for the aided and unaided conditions, respectively. While the trend is the same between the two studies, the average reaction times were much shorter in the current study. A similar pattern emerges when one examines the data reported by Gatehouse and Gordon (1990), who also reported hearing aid benefit for a reaction time measure. For performance conditions with speech recognition around 50%, the authors reported average response times of 550 and 719 ms for aided and unaided conditions, respectively.

Therefore, it is possible that hearing aids may, in fact, improve objective listening effort, but the task employed in the present study was not sensitive to changes in listening effort because the task was too easy; participants were very quick to respond relative to other studies that reported hearing aid benefit. One method of increasing task difficulty, and presumably test sensitivity, would be to increase the complexity of the secondary task. By employing a more complex secondary task, Sarampalis et al. (2009) reported a mean benefit of approximately 60 ms of activating noise reduction in the hearing aids during testing.

In addition to the simplicity of the task, and thus the relatively quick reaction times, the current study may not have demonstrated hearing aid benefit because there was substantial inter-participant variability. Participants had a wide range of hearing losses and hearing aid experiences. While all participants were fitted with appropriate amplification for their hearing loss for the purpose of study participation, not all had previous hearing aid experience. There is some evidence, at least for speech recognition, that hearing aid experience may impact performance. Several investigators have reported an acclimatization effect for speech recognition, especially in the first months following the hearing aid fitting (e.g., Cox & Alexander, 1992; Gatehouse, 1992; Horwitz & Turner, 1997), although not all studies have confirmed this effect (e.g., Bentler, et al., 1993; Humes & Wilson, 2003; Humes, et al., 2002; Saunders & Cienkowski, 1997). Therefore, although the role of hearing aid experience on listening effort has not yet been reported in the literature, it is possible that listeners who are accustomed to hearing aid use may be more likely to derive benefit from hearing aids for listening effort as well.   .

To exclude the role of hearing aid experience, a subsequent analysis of variance was completed by including only the 27 participants who had previous hearing aid experience and three within-subject variables (Hearing Aid, Visual Cues, Background Noise). When new hearing aid users were excluded from the analysis, there was a significant main effect of Hearing Aid ($F_{1,26} = 4.344$, $p < 0.05$), in addition to a main effect of Background Noise ($F_{1,26} = 4.311$, $p < 0.05$). In other words, hearing aids reduced listening effort but background noise increased listening effort. Although the effect was small (67 ms aided, 76 ms unaided), these results suggest that experienced hearing aid users do receive hearing aid benefit for reducing listening effort. However, acclimatization to amplification may be necessary before this benefit is achieved. Because there were no significant interactions, the hearing aid benefit may be independent of listening situation (auditory-only, auditory-visual, quiet, noise).

It was also of interest to examine the relationship between the potential predictive variables (working memory capacity, lipreading ability) and hearing aid benefit, while excluding the seven participants without hearing aid experiences. Using multiple regression on hearing aid benefit scores, results revealed that lipreading ability was significantly related to hearing aid benefit in quiet with AV stimuli ($\beta = -0.492$, $t(24) = 2.698$, $p < 0.05$). This finding is consistent with the analyses performed using data from all 36 participants (see Figure 7) and suggests that people who are better lipreaders get less hearing aid benefit than their peers in quiet when visual cues are present. Analyses also revealed a significant relationship between working memory capacity and hearing aid benefit in the AV noise stimuli ($\beta = 0.406$, $t(24) = 2.331$, $p < 0.05$).

These results suggest that, within the group of experienced hearing aid users, people with smaller working memory capacity derive more hearing aid benefit in background noise with AV stimuli (see Figure 10). While there was a trend for this relationship to be significant, visual inspection of Figure 10 reveals that working memory capacity is not very predictive of hearing aid benefit in noise with visual cues present when considering any single individual listener. Taken together, these results suggest that, on average, people who are experienced hearing aid users do get hearing aid benefit for listening effort, but predicting benefit for an individual, which is of considerable interest clinically, may be difficult. The most valuable variable in predicting benefit is lipreading ability in the AV quiet condition. However, it is clear that hearing aid experience likely plays a role in hearing aid benefit for listening effort.

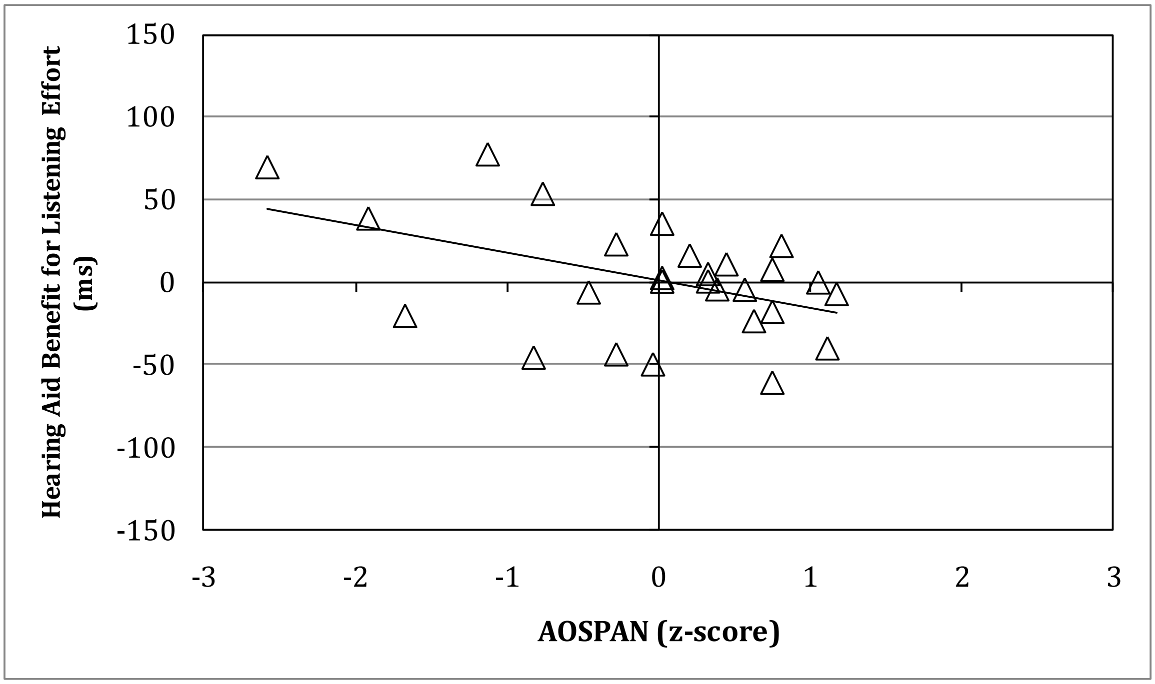

Figure 10. Relationship between working memory capacity and hearing aid benefit in noise in the auditory-visual condition. Benefit scores were calculated by subtracting the score in aided condition from the score in the unaided condition. Therefore, a positive benefit score indicates a faster reaction time and thus less listening effort.

The mechanism behind the potential influence of hearing aid experience is unclear. Perhaps participants who are fitted with hearing aids for the first time are overwhelmed by the new sounds and improved audibility. These new sounds may be distracting and limit the benefits for reducing listening effort. Furthermore, hearing aids often do not sound natural to first-time hearing aid wearers. New users may report that sounds seem unnatural or distorted. This unnaturalness or distortion may similarly interfere with hearing aid benefit for listening effort, although it may not interfere with speech recognition. More research is needed to evaluate the role of hearing aid experience on listening effort, particularly in regards to hearing aid benefit.

While previous hearing aid experience may have been a factor for listening effort, there may have been other variables that differentiated the two groups in addition to hearing aid experience. For example, there was a trend for the experienced hearing aid users to have more hearing loss than their inexperienced counterparts, pure-tone averages (500, 1000, 2000, and 4000 Hz) of 39.2 and 24.6 dB, for the experienced and new hearing aid users respectively. Furthermore, participants who were experienced users also required approximately 3 dB better SNR to achieve the criterion speech recognition performance in both the auditory-only and auditory-visual conditions. However, these differences were not statistically significant. Indeed, there were no significant differences between new and experienced hearing aid users with regard to lipreading ability, working memory capacity, pure-tone average, age, or SNR used during testing. While there were no statistically significant differences between new and experienced hearing aid users, there were only nine new users and the sample sizes were unequal. Future studies investigating listening effort and hearing aids should carefully consider participant’s hearing aid experience.

In addition to hearing aid experience, another inter-participant variable that was shown to influence hearing aid benefit for objective listening effort was lipreading ability (see Figure 7). There was a statistically significant relationship between lipreading and auditory-visual stimuli in quiet. This trend is generally the result of reduced unaided listening effort for people who were better lipreaders. Indeed, there is a significant correlation between lipreading ability, as measured by z-score on the ReSULT, and unaided listening effort, as measured by median AV quiet reaction time minus the baseline ($R^2 = 0.269$, $p < 0.01$). Perhaps because they are better at lipreading, listening in quiet to auditory-visual stimuli requires fewer cognitive resources. The addition of the hearing aid does not improve their listening effort because it was already low. Conversely, people who are not good at lipreading have more listening effort with the auditory-visual stimuli because they have hearing loss and because they have to expend cognitive resources to utilize the visual cues. Providing appropriately fit hearing aids can reduce listening effort for these individuals by reducing the effects of hearing loss. Conversely, providing appropriately fit hearing aids to people who are good lipreaders did not reduce listening effort because their listening effort was already low because they did not have to devote resources to using visual cues.

Because the main effects of hearing aids were small (7 ms), even for experienced users (9 ms), the task employed was not sensitive to factors that likely influence listening effort. As such, the task was likely also not sensitive to predictive variables that might predict benefit from hearing aids. Employing a task that elicits bigger effects might make the predictive variables more valuable for predicting hearing aid benefit.

Interestingly, there was no significant relationship between hearing aid benefit for listening effort and for speech recognition. Figure 11 displays hearing aid benefit for speech recognition as a function of hearing aid benefit for listening effort for auditory-only (top panels) and auditory-visual (bottom panels) conditions in quiet (left panels) and in background noise (right panels). Inspection of these figures reveals that there is a limited relationship between hearing aid benefit for speech recognition and for listening effort. Indeed, correlation analysis revealed no significant relationship between listening effort and speech recognition benefit. While many people derive hearing aid benefit on both dimensions, and only a few are hurt on both dimensions, some participants derive hearing aid benefit for speech recognition **or** listening effort, but not both. These results suggest that listening effort and speech recognition performance are distinct factors, and hearing aid use may impact each differently.

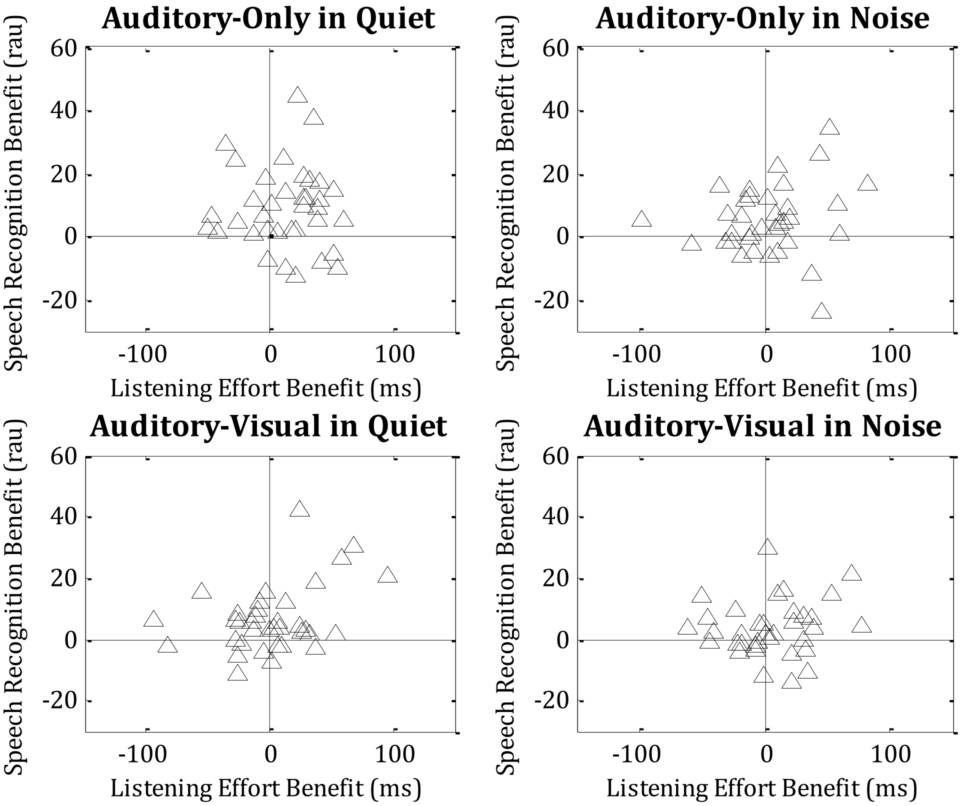

Figure 11. Hearing aid benefit for speech recognition (rau) as a function of hearing aid benefit for listening effort (ms) for individual participants in the four listening conditions. Top panels

display hearing aid benefit in auditory-only conditions, while the bottom panels display hearing aid benefit in auditory-visual conditions. Left panels display benefit in quiet, while right panels display benefit when background noise was present.

Visual Cues

When speech recognition performance was matched in auditory-only and auditory-visual conditions, there was no main effect of visual cues on listening effort, although in quiet, better lipreaders were more likely to derive benefit from the visual cues with the AV stimuli and reduce listening effort relative to the AO conditions (see Figure 9). These results are consistent with the findings of Picou, Ricketts, and Hornsby (in press) who investigated listening effort using a paired-associates recall task. The authors found that, while there was no main effect of visual cues, better lipreaders were more likely to derive benefit from visual cues.

In contrast to the findings of the current study, Picou et al reported that the effect of lipreading ability was only significant when background noise was present, but not in quiet. However, Picou et al tested participants with normal hearing, while the current study evaluated listeners with bilateral sensorineural hearing loss. It is possible that lipreading is only useful for predicting benefit from vision if there is one, and only one, additional factor that influences listening effort. Because background noise (Heinrich, et al., 2008; Murphy, et al., 2000; Rabbitt, 1968; Zekveld, et al., 2010), hearing loss (Hicks & Tharpe, 2002; McCoy, et al., 2005; Pichora-Fuller, et al., 1995; Rabbitt, 1991), and hearing aids (Downs, 1982; Gatehouse & Gordon, 1990) have all been shown to influence listening effort, perhaps only one of these can be present at a time when predicting benefit from visual cues for listening effort. In the case of the results reported by Picou et al, the lipreading only had predictive value when there was background noise present because the participants had normal hearing. In the case of the current study, lipreading only had predictive value in the quiet, unaided condition because the participants had hearing loss. Adding hearing aids or background noise may have increased the variability and reduced the predictive value of the lipreading score. Other potentially predictive variables should be investigated to evaluate if more of the variability can be explained when additional factors that influence listening effort are present.

Background Noise

Although the effect was small (~10 ms on average), background noise increased objective listening effort (see Figure 6). These results are consistent with much previous research suggesting that background noise increases listening effort as measured by slowed reaction times (Downs & Crum, 1978), poorer recall (Heinrich, et al., 2008; Murphy, et al., 2000; Rabbitt, 1968), or increased pupil dialation (Zekveld, et al., 2010). Although background noise increased listening effort, there were no predictive variables that successfully predicted susceptibility to noise. Perhaps other predictive variables (e.g., age, education, vocabulary, signal processing) might have predictive value and future studies should investigate if it is possible to predict people who are more likely to experience increased listening effort in background noise.

Because the effects, when present, of the variables of interest were generally small, it was also of interest to analyze the data logarithmically in case the perceptual data were not well described using linear relationships. To do this, a log transform of median reaction time for each participant was used in the same analyses as described above. However, the pattern of results was identical to that using the non-transformed reaction time data. Therefore, a logarithmic and a linear description described the data equally well.

Subjective Listening Effort

The subjective ratings of listening effort suggested that participants perceived listening effort benefit from hearing aids and visual cues, but these factors were not beneficial when the background noise was present (see Figure 9). However, further analyses revealed that the subjective ratings were very closely aligned with speech recognition performance and not objective measures of listening effort (see Figure 12). Indeed, the pattern of results for subjective ratings of listening effort is very similar to the one reported for speech recognition performance. Clearly, the reaction time measure and the subjective ratings are not indices of the same phenomenon called “listening effort.” The question, “how much effort did you put into hearing what was said,” may have been too vague. Or perhaps people have difficulty separating effort from performance. In any case, future work that seeks to investigate perceived listening effort should work to further refine questions that elicit responses that indicate “effort” and not just “performance.”

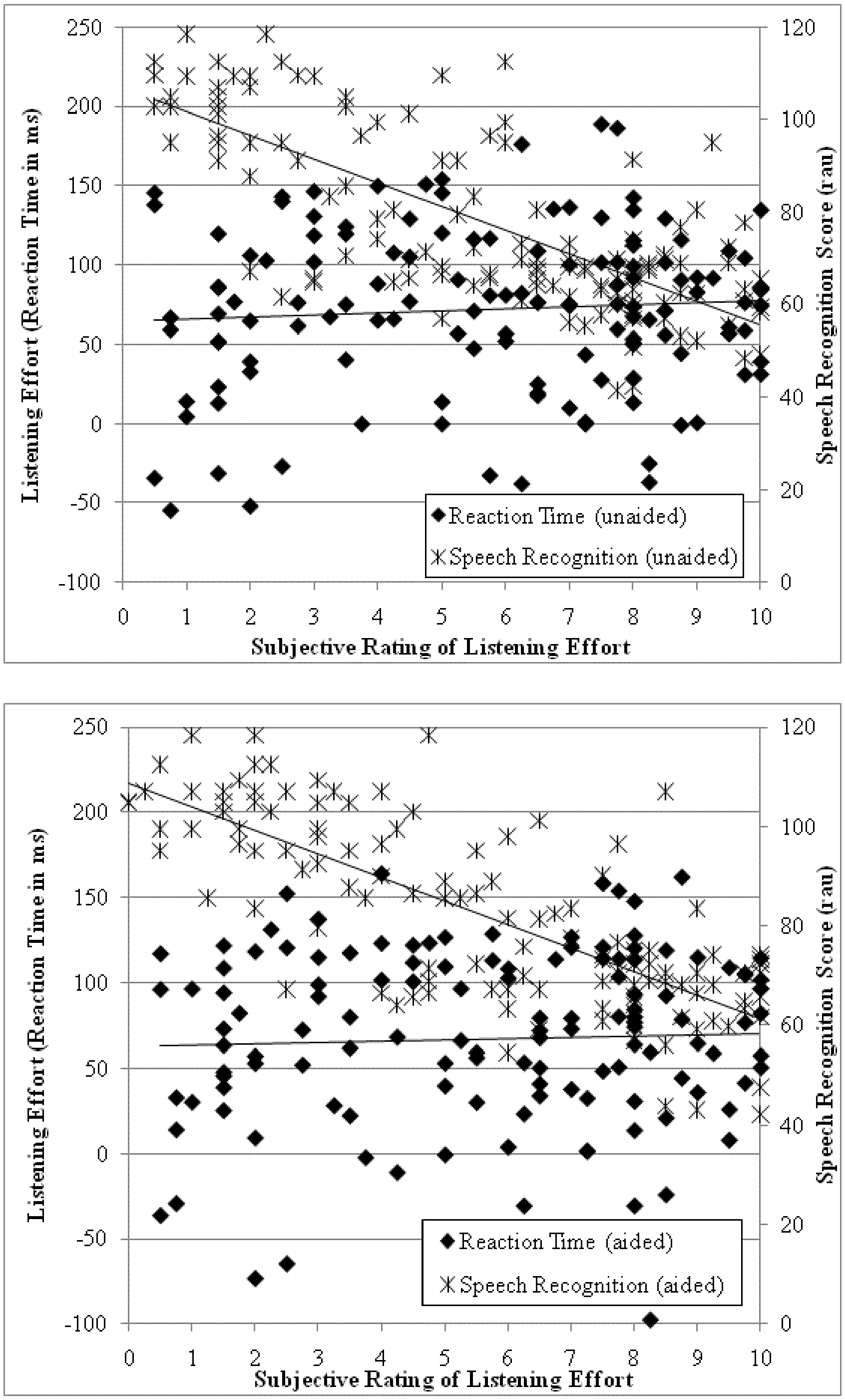

Figure 12. Relationships between subjective ratings of listening effort and objective measures of listening effort (filled diamonds) or speech recognition performance (asterisks) for all of the unaided conditions (top panel) and all of the aided conditions (bottom panel). Linear trend lines are displayed as well, but only the relationships between subjective ratings and speech recognition performance were significant.

CHAPTER V

CONCLUSIONS

In summary, the results of this study suggest that, on the average, hearing aids improve objective listening effort; however, this only occurs after a period of acclimatization. Furthermore, people who are not good lipreaders may also derive hearing aid benefit when using auditory-visual stimuli, generally because people who are good lipreaders expend less listening effort in the unaided condition. Therefore, the addition of the hearing aid provides little, if any, additional benefit for people who are good lipreaders. Good lipreaders are also more likely to derive benefit from the presence of visual cues than people who are not good at lipreading. However, there is no average effect of providing visual cues on objective measures of listening effort when speech recognition performance is matched in auditory-only and auditory-visual conditions. Background noise increased objective listening effort, but neither working memory capacity nor lipreading ability predicted susceptibility to noise. Finally, it should be noted that the magnitude of listening effort was generally small in this study, potentially obscuring the effects of predictive variables. Further investigation is needed to determine if other methods which include more complex secondary tasks result in greater measured listening effort effects.

With regards to subjective listening effort, the question, “how much effort did you have to put into hearing what was said,” elicited responses that were closely tied to speech recognition performance and not objective measures of listening effort. Therefore, future studies should further refine the method of assessing subjective listening effort.

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