COGNITIVE FACTORS AFFECTING HEARING

COGNITIVE AUDIOLOGY: INVESTIGATING THE EFFECTS OF COGNITIVE LOAD AND INDIVIDUAL DIFFERENCES IN COGNITIVE CAPACITY ON HEARING

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Lay Abstract

The ability to hear is affected by many factors, including attention and memory. The goal of this research is to investigate the cognitive factors (attention and memory) that affect hearing and how these effects differ on an individual level. My findings contribute to a better understanding of how background noise and mental demand affect hearing ability and listening effort, as well as how individual differences in cognitive ability further influence these factors. Results suggest that background noise and increased mental demand will decrease listening ability and increase listening effort. These changes in listening differ according to individual cognitive ability.

Abstract

Listening ability is affected by external factors such as background noise and internal factors such as attention-allocation. I varied listening conditions and cognitive load and evaluated auditory word recognition and ratings of listening effort. Additionally, I investigated how individual differences in working memory capacity affected word recognition, recall, listening effort, and how working memory capacity interacted with other factors. Rönnberg et al.'s (2013) Ease of Language Understanding (ELU) model states that individual differences in working memory capacity will lead to differences in language comprehension in challenging listening conditions, where those with higher working memory capacity will be better at speech recognition. Using a dual-task experiment, participants heard and repeated words presented in three listening conditions: masked with pink noise, masked with babble, and processed through a hearing loss simulator. To manipulate cognitive load, participants completed the speech recognition task in both single- and dual-task paradigms. In the dual-task paradigm, participants continuously tracked a pseudo-randomly moving target on a screen for half the experiment. Participants reported perceived listening effort for each combination of listening condition and tracking condition. Additionally, memory for correctly heard words was tested with a recognition memory test. Word recognition performance and listening effort rating data agreed with my hypotheses that difficult listening conditions would produce poorer word recognition performance and increased listening effort. Interesting effects of cognitive load are discussed. The relation between working memory capacity and performance on various measures is also discussed in the context of the

ELU model and theories of working memory capacity. Internal and external factors clearly interact to affect listening, and this interaction varies across individuals.

Key words: Audition, working memory, working memory capacity, dual-task, listening effort, divided attention, cognitive load

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Declaration of Academic Achievement

This thesis consists of an experiment designed to investigate the effects of cognitive factors and individual cognitive capacity on hearing ability and listening effort. I am the author of this thesis and will be the first author of possible peer-reviewed papers related to this work that may be submitted in the future. The experiment was developed in collaboration with my M.Sc. supervisor Scott Watter, committee member Karin Humphreys, and external researcher Jeff Crukley. Data were analyzed in collaboration with my supervisor. I, including revisions from my supervisor, Jeff Crukley, and my M.Sc. committee, authored all written work on this thesis.

Introduction

Language is how we communicate. Speaking, listening, and understanding are integral to our relationships and culture. This is why hearing is so important. This is also why it is important for us to understand how we hear and what can affect our hearing. Although the physical ability of the ear is essential for hearing, there are many other factors that need to be considered in hearing-related research. There are a wide range of cognitive abilities that affect hearing, in addition to the physical effects of hearing loss. With increasing stimulus intelligibility, auditory word recognition improves, but with increasing memory load, this ability declines (Francis & Nusbaum, 2009). Additional cognitive load at the time of speech processing will impair speech recognition, context will aid speech recognition, and background noise will impair later memory compared to words heard in quiet (Davis & Johnsrude, 2007; Mitterer & Mattys, 2017; Murphy, Craik, Li & Schneider, 2000; Piquado, Cousins, Wingfield & Miller, 2010; Wingfield, Alexander & Cavigelli, 1994; Wingfield & Tun, 2007). These findings reflect the hearing conditions we experience every day, where the intelligibility of what we're listening to changes with changing background noise and we listen while doing other tasks and use other cues, including context, to aid in understanding what we hear. While these findings reflect everyday life, they get a lot more complicated when other common factors are also considered.

Many of these cognitive effects are further influenced by aging and hearing loss. Even accounting for hearing loss, aging comes with its own changes in speech perception (Pichora-Fuller & Souza, 2003). Hearing sensitivity and cognitive ability decline with age, compounding to further affect speech recognition (Wayne & Johnsrude, 2015). These declines affect the processing resources that are available for speech recognition (Tun, Williams, Small & Hafter, 2012). As cognitive resources decline, the resources required to process the signal may outnumber those that are available, especially if a listener has hearing loss or if the listening conditions are demanding. With hearing loss, more resources must be used to process the signal itself, leaving fewer to process the information, resulting in poorer speech recognition. Cognitive ability, and its changes with aging, can exaggerate the effects of hearing loss, but studies have also shown that hearing loss can affect cognitive ability. In fact, the relation between hearing loss and cognitive ability is a two-way street; a longitudinal study by Lin et al. (2011) found that increased degree of hearing loss is associated with poorer performance on measures of cognitive ability. Furthermore, a recent animal study found a causal link between cognitive ability and hearing loss, where mice with induced hearing loss early in life had worse cognitive ability compared to those with normal hearing (Park et al., 2016).

In addition to aging and hearing loss affecting the cognitive resources available for speech recognition, the extent of these resources naturally differs between people, further affecting speech recognition on an individual level. Akeroyd's (2008) review of twenty studies on individuals with normal and impaired hearing found a connection between individual differences in cognitive ability and speech perception ability. Working memory was a strong measure of cognitive ability and was predictive of speech perception. Individuals differ in their working memory capacity and a growing body of research suggests these differences impact hearing ability (Daneman & Carpenter, 1980;

Engle, Tuholski, Laughlin & Conway, 1999). Individuals with higher working memory capacity perform better in speech recognition tasks and have better memory for words presented in noise than those with lower working memory capacity (Kjellberg, Ljung & Hallman, 2008; Ljung, Israelsson & Hygge, 2013; Rudner, Rönnberg & Lunner, 2011). These differences in hearing ability have often been studied in conjunction with hearing aids; those with higher working memory capacity get more benefit out of hearing aid use (Akeroyd, 2008). Participants with higher working memory capacity are better able to compensate for the signal modifications inherent to hearing aid signal processing than participants with lower working memory capacity. One benefit of this compensation ability is the lower degree of listening effort expended by those with higher working memory capacity (Besser, Koelewijn, Zekveld, Kramer & Festen, 2013; Classon, Rudner & Rönnberg, 2013; Desjardins & Doherty, 2014; Lunner & Sundewall-Thorén, 2007; Souza, Arehart, Shen, Anderson & Kates, 2015). In fact, focusing on cognitive skills, rather than sensory decline, may be more beneficial in helping those with hearing loss (Ferguson & Henshaw, 2015; Pichora-Fuller & Singh, 2006). Those with higher working memory capacity have more resources available to compensate for detrimental factors, such as hearing loss, background noise, and cognitive loads, and therefore can better allocate those resources to understanding what they are hearing (Meister, Schreitmüller, Ortmann, Rählmann & Walger, 2016; Tun, Williams, Small & Hafter, 2012).

Rönnberg et al. (2013) explains the relation between working memory and speech perception with their Ease of Language Understanding (ELU) model. It states that individual differences in working memory capacity lead to the differences in language comprehension ability, and those with higher working memory capacity will be better at speech recognition, due to having more resources available to process the incoming information. A higher capacity means that when a large portion of cognitive resources are required for earlier steps in the stream of information processing, adequate resources remain available for later processing, including understanding, using, and encoding the information. Support for this model comes from a review by Wingfield, Amichetti, and Lash (2015) in which they highlight the model's integration of the factors affecting hearing as its strength. These authors succinctly sum up the ELU as a hypothesis that explains the interaction of sensory input, prior knowledge, and working memory, and how these individual factors relate to the ease with which language is understood. Their review supports the model's claim regarding the importance of working memory—and specifically the individual differences in it—and its role in understanding spoken language. Further support comes from studies that have investigated the effects of cognitive factors on hearing, and the findings can be explained by the availability and use of cognitive resources. When sensory input is degraded, it becomes more difficult to process; overcoming this difficulty consumes resources, which then limits the amount available for later, downstream processing (Kahneman, 1973; Wingfield, 2016). This allocation of resources means there are fewer available for processing the meaning of the word, and so word recognition declines (Pichora-Fuller, Schneider & Daneman, 1995). Older adults, who have fewer cognitive resources, rely more on sentence context in speech recognition than younger adults (Wingfield & Tun, 2001). Providing semantic context eases the demands of earlier processing stages and in turn leaves resources available for speech recognition. Winn, Rhone, Catterjee & Idsardi (2013) demonstrated that individuals with cochlear implants use different strategies than individuals with normal hearing. Cochlear implant users relied more on context and other cues to understand speech.

An additional model used to explain the interaction of cognitive demands and cognitive capacity in listening is the recently-developed Framework for Understanding Effortful Listening (FUEL; Pichora-Fuller, et al., 2016). This framework further seeks to understand how individual cognitive ability interacts with cognitive factors to affect a listener's effort as well as their hearing ability. The FUEL claims that a candidate way to test these interactions is through cognitive behavioural measures, such as working memory, which can be evaluated by the reading span and n-backs. The Framework further endorses the use of accuracy and reaction time in dual-task paradigms to assess attention and processing speed in conjunction with listening. This way, a variety of factors and measures can be used and assessed in conjunction to determine the influence of individual cognitive ability, as well as the effects of external cognitive demands.

Rönnberg, Rudner, Lunner, and Stenfelt (2014b) conducted a study to determine how different types of background noise and signal-to-noise ratios affect listening effort, and how this effect is related to working memory in normal-hearing young adults. Sentences were presented in different background noises (maskers) while varying levels of signal-to-noise ratio (SNR). Speech recognition and memory were assessed by asking questions about the sentences. Listening effort was measured by performance on the questions, where poorer performance meant listening was more effortful. The reading span test was used to measure working memory capacity and the letter memory test was used to measure executive function. They found that as long as the intelligibility of the words remained high (a high SNR), the type of masker did not affect memory performance. As the SNR decreased, however, memory performance declined across masker type. The authors relate their findings to the concept of cognitive spare capacity; as the signal decreases, the cognitive load is increased and more cognitive capacity is required to process the signal leaving less capacity available for memory encoding. The relation between SNR and memory performance was especially true when the background noise was unintelligible speech, which, the authors state, can add cognitive load by potentially providing some level of informational masking. This type of masking makes the signal processing even more difficult, and thus takes even more cognitive capacity from the memory processing. Speech recognition and memory decreased with increasing memory load. Again, this was expected given that cognitive load earlier in processing will come at a cost to downstream processing. Reading span scores were also correlated with memory, where higher working memory capacity was positively related with better memory scores on the sentence questions. The letter memory test, however, did not correlate with memory, leading the authors to conclude that executive function does not impact listening performance in the same way that working memory does. This aligns with theories that claim working memory and executive function are different constructs of overall executive attention and cognitive control, and are often separately assessed through the use of different tests (McCabe, Roediger, McDaniel, Balota & Hambrick, 2010). Overall, Rönnberg et al. (2014b) concluded that a variety of factors can make listening more difficult, and that as listening conditions get more difficult, those with higher working memory capacity are better able to cope with the difficulty, and therefore perform better overall.

Dual-task experiments are often used to assess listening effort in hearing studies because the secondary task provides interference with processing of the primary task (Gagné, Besser & Lemke, 2017). This interference results in the secondary task reflecting listening effort while also allowing experimenters to assess these effects while manipulating other factors of the listening conditions. Desjardins and Doherty (2013) conducted a dual-task listening study with both younger and older adults with normal hearing, as well as with older adults with hearing impairment. Participants identified the last word in a masked sentence while simultaneously completing a digital pursuit rotor-tracking test. Listening effort was measured as performance on the secondary (tracking) task, where poorer performance indicates greater listening effort. In addition to these tasks, participants were tested on a series of cognitive tests, including the reading span, digit symbol substitution, and the Stroop task, which measure working memory capacity, processing speed, and selective attention, respectively. Better scores on working memory and processing speed were related to better recognition of speech in noise; listening effort was negatively correlated with working memory and processing speed; older adults required even more favourable SNRs to maintain listening accuracy; and performance was overall better on high context sentences (compared to low context). All these findings are in line with the ELU model and the prediction that individual differences in working memory and the allocation of resources are reflected in performance on other measures.

Present Study

The connection between cognitive factors and hearing ability is well established. To date, several studies have combined manipulations of cognitive load and measures of listening effort with word recognition, but the nature and extent of these interactions need further investigation. The present experiment aimed to further study how cognitive load, word recognition in background noise, listening effort, and individual working memory interact. I used a dual-task paradigm (similar to that of Desjardins & Doherty, 2013) where participants performed an auditory word recognition task while simultaneously performing a motor tracking task. I evaluated the effects of signal modification and cognitive load on word recognition, secondary task performance, and listening effort. Listening conditions were speech combined with pink noise, combined with four-talker babble, or processed through a hearing loss simulator. The study was conducted with normal-hearing undergraduate students, but the use of a simulated hearing loss condition provided a condition of sensory hearing analogous to that of an older adult: the amplitude was attenuated at higher frequencies to approximate age-related hearing loss. The secondary motor tracking task let me manipulate cognitive load through single- and dual-task conditions (no load and high load, respectively). The motor task, consisting of tracking of a pseudo-randomly moving target, provided a continuous measure in which dual-task costs were reflected (Lochner & Trick, 2014). Subjective listening effort was measured to see how effort changed with changing cognitive loads and listening conditions. A recognition memory test was given to test later memory for the correctly identified words in the first phase (listening) of the experiment. I also measured working memory capacity to see the interactions of individual cognitive ability and how it related to other cognitive measures. I took both reading span and operation span measures of working memory capacity.

Based on previous findings in the literature regarding the allocation of cognitive resources, I had several expected results. I expected word recognition performance to decline as the listening condition became more difficult. I also expected to see an effect of the listening condition reflected in the secondary (tracking) task, where the allocation of resources to the listening task would result in poorer secondary performance as the listening condition became more difficult. I expected listening effort to follow the same pattern as word recognition and tracking accuracy; as the listening condition became more difficult, ratings of effort would increase. For the recognition memory test, I expected poorer memory for the words heard in the more difficult listening conditions and for those words heard while tracking. Once again, this is because the division of resources at the earlier stages of processing (hearing the words) would affect later processing (encoding the words). The more difficult listening conditions and the divided attention conditions would leave fewer resources available for memory encoding, and lead to worse recognition of the presented words.

Of greatest interest in this study, I had predictions regarding how individual working memory capacity affects all these measures (listening performance, dual-task costs, listening effort). I expected that participants with higher working memory capacity would be less affected by difficult listening conditions and cognitive loads, meaning they would perform better on both the listening and tracking tasks than those with lower working memory scores. This is because their greater cognitive ability provided more resources to devote to both tasks, as well as being better able to allocate resources than those with lower working memory capacity. I also expected those with higher working memory capacity to rate the listening as less effortful due to having more resources to devote to the tasks compared to those with lower working memory capacity. Lastly, I expected those with higher working memory capacity to perform better on the recognition memory test because, once again, they have more resources to devote to encoding the information downstream, and would therefore have better memory for the words they correctly heard in the listening task. If correct, these predictions would be seen in correlations between working memory scores and the other task measures. If working memory positively correlates with word recognition and recognition memory, and negatively correlates with tracking errors and listening effort, then the hypothesis will be supported.

Overall, I expected to see tradeoffs in performance and effort ratings, and for these tradeoffs to differ with individual working memory capacity, because the allocation of cognitive resources will change with changing task demands, and these resources depend on an individual's cognitive ability.

Method

Participants

Forty-five participants (34 female, mean age = 19.87) were recruited from McMaster University's undergraduate population and received partial psychology course credit for their participation. All participants had self-reported normal hearing.

Apparatus and Stimuli

The visual stimuli were presented on a Dell UltraSharp 2001FP LCD 17-inch monitor running from an HP Pro 3130 MT computer, using Presentation® software. The target stimulus was a red circle, 1-inch in diameter, and the participant-controlled hoop was blue and 1.5-inch diameter. The circle moved pseudo-randomly around the screen, its movement determined by combining out-of-phase sine waves. This produced a random-appearing movement that was difficult to predict. Participants used a Logitech ATK3 joystick controller to control the movement of the hoop. Participants were seated approximately 60cm from the computer monitor and used a standard keyboard to progress through blocks of the experiment. The words in the surprise recognition memory test were centered on the screen and presented in white, size 24 Arial font. Participants responded to the words using a standard keyboard.

The auditory stimuli were presented over a Mackie CR3 Creative Reference Multimedia Monitor speaker running from an HP Pro 3130 MT computer or with AKG K 44 over-ear headphones, at 70dB, also through Presentation® software. Twenty-five participants (1 to 22, 33 to 34, and 45) completed the listening task using headphones (19 female, mean age = 19.72). The other twenty participants (23 to 32 and 35 to 44) completed the task using the speaker (15 female, mean age = 20.5). I switched between these two methods because the experimental setup required switching between two experiment rooms while the apparatus was being set up and then subsequently adjusted. The participants ran with headphones were in a room with louder background noise (due to ventilation) and thus required the use of headphones to maintain the volume of the target stimuli at 70dB. The other experiment room that was used was quieter and the 70dB volume of stimuli was achieved without the use of headphones. The decision to switch between experiment rooms, and consequently methods of presenting the stimuli, came out of necessity while the experimental setup was being determined and finalized. The stimuli were The Northwestern University Auditory Test Number 6 (NU6) list which are made up of a single-speaker saying a word, preceded with a carrier phrase: 'say the word'. Sentences were combined with pink noise, four-talker babble, or processed through a hearing loss simulator to create three different listening conditions. Pink noise condition was constructed in MATLAB, using code developed by Hristo Zhivomirov (2013; see Appendix A). The NU-6 were set to 9dB higher than the pink noise (9 dB SNR). The four-talker babble track was produced by Auditec (1971). The NU-6 were set to 3 dB higher than the babble (3 dB SNR). Hearing loss associated with normal aging was simulated by attenuating the stimulus amplitude at a range of frequencies (see Appendix B for a simulated audiogram of the hearing loss simulator). Verbal responses to the auditory stimuli were manually recorded into excel by the experimenter in real-time.

The Operation Span and Reading Span tasks were used with permission from the Attention and Working Memory Lab at Georgia Institute of Technology (Foster et al., 2015; Oswald, McAbee, Redick & Hambrick, 2015). They were fully automated and provided participants with instructions on-screen.

Design

All participants completed the experimental tasks in the following order: listening task (tracking and repeating auditory stimuli), surprise recognition memory test, Operation Span, Reading Span.

The listening task consisted of 12 blocks of 16 auditory trials (for a total of 192 words). The blocks alternated between no-tracking and tracking, with listening conditions counterbalanced across words lists, and word lists counterbalanced across participants. Before each no-tracking block, participants were given two minutes of tracking practice, to orient them to the task. The practice was given before the no-tracking blocks in order to prevent the carry-over of the practice into the tracking blocks; this way, participants started the task fresh each tracking block and it prevented fatigue by spacing out the practice from the tracking blocks. Subjective listening effort was rated after every block, according to the scale developed by Johnson, Xu, Cox & Pendergraft (2015; see Appendix C). It is important to note that the experimenter used specific wording when prompting the participant for their listening effort. The question was worded such that the participant was asked specifically for how effortful it was to listen to and identify the words; they were not asked about how difficult the task was, how much effort the experiment was, nor how hard it was to hear. This ensured that listening effort in the primary task (listening and repeating the words), specifically, was measured.

Each trial was approximately five seconds in duration, with the background noise in the Pink Noise and Babble conditions coming on at one second, and the target word occurring at two seconds for all three listening conditions. There were 16 trials in each block, all of which were the same listening condition; therefore participants completed four blocks of each listening condition, starting with a block of pink noise and followed by the blocks of babble and simulated hearing loss counterbalanced across participants. Participants started with a two-minute tracking practice, followed by the first block of 16 trials. After each block, they were given a rest period of up to two minutes. The blocks alternated between no-tracking and tracking, with listening condition counterbalanced across them, and a tracking practice before each no-tracking block.

Procedure

Single Task For the no-tracking blocks, participants merely sat in front of the computer, listening to the stimuli presented in either Pink Noise, Four-Talker Babble, or Simulated Hearing Loss, and repeated the word out loud. This was recorded by the experimenter as either correct or incorrect, and, if incorrect, the spoken word was also written down. There were two blocks of each listening condition in the no-tracking blocks, making six blocks of no tracking alternating with six blocks of tracking. The participants were instructed to say the word loudly and clearly after hearing the sentence. After each block, participants rated their subjective listening effort using the scale seen in Appendix C.

Dual task For the tracking blocks, participants followed the same procedure in the no-tracking blocks except they had the additional task of tracking the moving red target with the blue hoop, using the joystick to control the hoop. They were again asked to repeat the word aloud and to rate their listening effort after each block. The blocks of tracking alternated with the blocks of no-tracking, for a total of twelve blocks all together.

Recognition Memory Following the listening task, participants were given a surprise recognition memory test. Participants indicated, using two keys on a standard keyboard, whether the word presented on the screen was 'old', meaning they heard it in the listening task, or 'new', meaning they hadn't heard it in the listening task. The list of 'new' words was linguistically matched to the list of old words. The 'old' words were the list of words the participant correctly identified in the listening task. This ensured that only words the participant was able to hear and correctly identify were included as 'old' words, in order to avoid compounding memory results with word recognition.

Operation span After completing the memory test, participants completed the Operation Span task. In this task, participants were presented with math equations (e.g. 5 + 2 = 8) and were to indicate, using a right or left mouse click, if the equation was true or false (the example provided being false). Beneath the equation, a letter was presented. Participants were instructed to remember the letter. After two to seven trials (equation followed by letter), depending on the block, a matrix of letters appeared on the screen and participants clicked them in the order they appeared, leaving blanks for ones they were unsure of. They did this for a total of 15 blocks.

Reading span Following the Operation Span, participants completed the Reading Span task. This task had a similar structure to the operation span. Participants were presented with sentences (e.g. The girl couldn't cross the road because of the cloud) and were to indicate, again using the mouse, whether the sentence made sense semantically (the example provided above does not make sense). The participant was told to remember the letter that was presented beneath the sentence and to choose the letters in the correct order from the matrix presented to them at the end of each block. They did this for 6 blocks.

Data Analysis

Data were analyzed using a separate repeated measures analysis of variance (mANOVA) for each independent measure: including word recognition accuracy and subjective listening in the primary (listening) task, and average tracking error and variance of tracking error in the secondary (tracking) task. Word recognition was measured in percentage of words correctly repeated in each condition. Listening effort was measured as the average rating of effort per condition. Both word recognition and listening effort were submitted to a 2 (tracking versus no-tracking) x 3 (Pink Noise versus Babble versus Hearing Loss) ANOVA, with both tracking condition and listening condition as within subjects variables. Average and variance tracking error were measured in pixel distance between the centre of the target and the centre of the hoop. These were submitted to a one-way (Pink Noise versus Babble versus Hearing Loss) within subjects ANOVA.

For the recognition memory test, d' scores were calculated using the hit rate on 'old' words in each condition and the overall false alarm rate. These were submitted to a

2 (tracking versus no-tracking) x 3 (Pink Noise versus Babble versus Hearing Loss) ANOVA.

Reading Span and Operation Span scores were calculated using the partial-credit unit score (Conway et al., 2005). Average scores were calculated and correlated with the other dependent measures.

Results

Headphones vs. Speakers

There were two methods used to present the auditory stimuli (headphones and speaker), so a check was done to ensure that these two methods didn't result in differences between the groups of participants. There were no significant differences on any of the dependent measures between participants who were presented with words over headphones and participants who were presented with words over speakers. The participant data, therefore, were collapsed across headphones/speaker.

Word Recognition

Average word recognition accuracy in each condition is shown in Figure 1. The ANOVA indicated a main effect of listening condition, $F(2,88) = 723.346$, $p < 0.001$. Participants were significantly better at recognizing the words in pink noise than in babble, and in babble than in simulated hearing loss. There was also a main effect of tracking condition, $F(1,44) = 6.619$, $p = 0.014$, which was driven by the difference in the babble listening conditions, $t(44) = 10.41$, $p < 0.001$, where the accuracy in the no-tracking condition (72.71%) was significantly lower than the accuracy in the tracking condition (77.57%). Averages by condition are shown in Table 1.

Subjective Listening Effort

Average effort ratings by condition are shown in Figure 2. The ANOVA indicated a main effect of listening condition, $F(2,88) = 112.70$, $p < 0.001$, where effort was greater for simulated hearing loss than for babble, and greater for babble than for pink noise. There was no effect of tracking condition. There was an interaction between listening and tracking conditions, $F(2,88) = 7.77$, $p= 0.001$, driven by a significant difference between ratings in the hearing loss condition, $t(44) = 3.13$, $p = 0.003$, where the average rating in the no-tracking condition (5.89) was significantly higher than the rating in the tracking condition (5.54). Average ratings by condition are shown in Table 1.

Tracking Error

Average tracking errors and standard deviation tracking errors were run in separate ANOVAs but are shown together in Figure 3. Both average error and standard deviation error showed main effects of listening condition, $F(2,88) = 25.362$, $p < 0.001$, and $F(2,88) = 13.135$, $p = <0.001$, respectively. There were significantly more errors in the simulated hearing loss condition than in the babble condition, as well as significantly more errors in babble than in pink noise.

Table 1 shows average and standard deviation of tracking error by listening condition. Figures 5 and 6 display average tracking error and standard deviation of tracking error, respectively, over the time-course of the trial.

Recognition Memory

Twenty-four participants were excluded from recognition memory analysis due to technical difficulties at the beginning of data collection (participants 1 to 24 were not included in analysis). For the remaining 21 participants (participants 25 to 45; 14 female, mean age = 20.05), recognition memory d' scores were calculated using hit rates for each condition and an overall false alarm rate for new presented words. d' memory accuracy scores are shown in Figure 4. There were no effects of listening condition, tracking condition, or an interaction between conditions, $F(2,40) = 0.124$, $p = 0.883$, $F(1,20) = 0.258$, $p = 0.617$, and $F(2,40) = 0.321$, $p = 0.727$, respectively. When d' scores were divided into high-scoring and low-scoring participants using a median split, there were still no main effect or interaction in either group. Similarly, when participants were divided into high-scoring and low-scoring reading span working memory scores, there were no main effects or interaction in either group.

Working Memory Correlations

Reading span and operation span scores were positively correlated, $r = 0.616$, $n = 45$, $p < 0.001$, as seen in Figure 7. Those who scored high on the reading span also scored high on the operation span, and vice versa. Reading span scores negatively correlated with average tracking error in the simulated hearing loss listening condition, $r = -0.386$, $n = 45$, $p = 0.009$, as well as standard deviation of tracking error in the simulated hearing loss listening condition, $r = -0.400$, $n = 45$, $p =0.007$, where those with higher reading span scores had lower average tracking errors and standard deviations in tracking errors (Figures 8 and 9). Reading span also negatively correlated with subjective ratings of listening effort in the dual-task pink noise listening condition (listening while tracking), $r = - 0.358$, $n = 45$, $p = 0.016$, as shown in Figure 10. No other significant correlations with working memory were found.

Discussion

My findings demonstrated a trading relationship in the allocation of cognitive resources while listening to words in noise and performing a secondary task. They also demonstrated how these tradeoffs affected listening effort and were mediated by individual working memory. Word recognition and secondary task performance declined when the listening condition became more difficult. This difficulty was further reflected in increased ratings of effort when the listening condition difficulty was increased. Working memory scores correlated with other measures, showing that individual differences in cognitive capacity can be seen in secondary task performance and listening effort. These findings align with the predictions and explanations of the ELU model. Furthermore, the methods used align with those proposed by Pichora-Fuller et al.'s (2016) FUEL model, and serve to test these measures concurrently in order to get a fuller picture of how they interact. My results reflected the consequences of dividing resources and furthermore showed that individual differences in working memory affected performance on a variety of cognitive measures.

Performance on both the word recognition (primary) and the tracking (secondary) tasks was as expected, given the previously observed effects of background noise and divided attention on performance. When the listening condition became more difficult, word recognition declined; the harder it was to hear the words, the worse participants performed. The different levels of listening condition also affected secondary task performance. It is interesting to note that even with the decline in recognition performance as the listening difficulty increased, there was also a parallel decline in tracking performance. This indicates that while a difficult listening condition will affect listening ability, it will also affect performance on secondary tasks. That is to say, the detriments of a difficult listening environment are not constrained to listening performance, but instead spread to other tasks. This is due to the division of cognitive resources, where when more resources are allocated to listening, as is the case when the background noise gets more difficult, there are fewer resources that can be allocated to the secondary task, which then suffers. Subjective listening effort reflects the word recognition and tracking performance patterns, where the listening conditions are rated as more effortful as the background noise difficulty increases. Again, this is as expected; increased noise difficulty should result in higher ratings of effort due to requiring more cognitive resources and attention to hear and understand. Additionally, the decline in tracking performance across increasing listening difficulty reflects the increasing listening effort, aligning with previous research that has found dual-task performance to reflect listening effort (Gangé, Besser & Lemke, 2017).

In both word recognition accuracy and subjective listening effort, there is an interesting and counter-intuitive reversal between tracking and no tracking in word recognition and effort ratings. Word recognition accuracy was higher in the tracking condition than in the no-tracking condition, but only in the babble listening condition. Overall, performance on the tracking task reflects the difficulty in the listening task, but this doesn't explain why the secondary task is affecting performance on the primary task. Usually, performance on the secondary task (tracking) is seen as an index of primary task (word recognition) difficulty, not the other way around. The primary task was not expected to reflect the difficulty of the secondary task, but it did in the babble listening condition. The fact that we seen an unexpected effect of dual-task on the listening task indicates that our results may have been influenced by additional factors. In fact, the effects of the secondary task on word recognition accuracy in the babble condition are counter to what one would expect to happen when attention is divided. Participants were more accurate at identifying the words when they were simultaneously tracking than when they weren't tracking. This contradicts the idea that dividing attentional resources would negatively affect performance. Similarly, ratings of listening effort should not be affected by the secondary task because the ratings aimed to measure listening effort, not overall task effort. Yet again, we see in the listening effort ratings a counterintuitive reversal in one listening condition; the secondary task, if it was to have an effect at all, should have had the opposite effect to what was seen. Instead, the results indicate that listening while tracking was less effortful than listening while not tracking, in the simulated hearing loss condition. To summarize these interesting findings before providing a possible explanation: there were unexpected effects of the secondary task on the primary task and on ratings of listening effort. In addition to this, the unexpected effects are opposite to what one would intuitively predict if such effects were to occur. Differences in attention allocation and motivation could explain these contradictory findings, instead of resource allocation. It may be a matter of task engagement, where the easiest listening condition doesn't require much engagement to do well and the hardest requires a lot of task engagement. In both cases, there would be no differences in word recognition between tracking and no tracking conditions, but for opposite reasons; the easiest listening condition because it's easy enough whether participants are tracking or not, and the hardest listening condition because the listening difficulty is equally difficult whether participants are tracking or not (additional cognitive load had no effect because the task was already very difficult). The babble condition, however, engaged participants at a middling level, where tracking then had an effect. The addition of the secondary cognitive load provided an attentional enhancement compared to no additional load, which then improved word recognition performance. Adding the secondary task made a difference in the babble condition because listening wasn't too easy or too hard, and therefore the additional cognitive load was able to affect primary task performance. The reversal in subjective listening effort rating followed a similar trend: tracking in the hearing loss simulation provided participants with better focus on the task, which translated to a lower rating of effort. This was not so in the pink noise and babble conditions because these conditions were already easy enough, despite their differences in word recognition accuracy. Again, the secondary task should not have affected listening effort ratings at all, but the engagement of attentional resources may provide an explanation for the observed results. The babble and hearing loss simulation conditions showed an interesting trade-off in attention and task difficulty, where the level of difficulty may have facilitated optimal attention-allocation despite differences in resource allocation. These findings provide insight to real-world listening; there may be specific listening difficulties, including background noise and attention allocation, that optimize listening performance and minimize listening effort. These are interactions and conditions that need further study in order to understand how listening ability and effort change with real-world listening conditions.

These observed tradeoffs additionally bring up the question of listener motivation. A recent area of interest in both listening accuracy and listening effort is how these measures change with a listener's willingness to attend. Motivation to listen changes with changes in the demand of the task, as well as with differences in individual and circumstantial motivation (Mackersie & Calderon-Moultrie, 2016; Pichora-Fuller et al., 2016). Dual-task conditions may provide enough engagement in more difficult conditions to provide sufficient motivation to perform better, as well as to make the primary task seem less effortful. However, there is likely a balance to strike between difficulty and motivation. If a task is too easy, and therefore boring, there may not be proper motivation to remain engaged in the task. If it is too difficult, the task runs the risk of participants giving up. For tasks with fixed difficulty, as in the current experiment, participant effort engagement depends on task difficulty; when the difficulty increases too much and success becomes less likely, participants will withdraw effort (Richter, Gendolla & Write, 2016). These changes in motivation will change resource and attention allocation and can explain the unexpected switches in the two conditions mentioned above. The more difficult, dual-task conditions led to more motivation than the single-task counter-parts, and therefore led to better performance and lower effort ratings.

While differences in listening condition difficulty can be seen in average tracking performance, the tracking task also provided a continuous demonstration of secondary task costs. As seen in Figures 5 and 6, the differences between the listening conditions can be seen in the seconds following stimulus onset. A difference of note is that the tracking errors in pink noise and babble diverge approximately 1.5-2.0 seconds after stimulus onset, a point in the time course where the participant would be listening to and then repeating the presented word. There was a lower level of error in the pink noise condition than in the babble condition at these time points. There was a higher level of error in the simulated hearing loss condition, across the entire time course than the other two listening conditions, indicating that this condition, overall, was more difficult for participants. This suggests participants were putting more focus and cognitive attention to the listening task because it was a significantly more difficult condition, and the effect of this is seen in poorer performance in the tracking task, as found in the review of dual-tasks and listening effort by Gagné, Besser and Lemke (2017).

The recognition memory test showed no effects of any condition, despite there being significant effects on the other measures. This lack of effect persisted when recognition memory scores were split between high- and low-scoring participants, as well as when participants were split between high- and low-scoring working memory participants. This finding contradicts previous studies, in which increasingly difficult background noise, as well as changes in cognitive load, have been found to affect later memory for presented words (Marsh, Ljung, Nöstl, Threadgold & Campbell, 2015; Rönnberg, Rudner, Lunner & Stenfelt, 2014a). Data from high and low working memory capacity participants were were analyzed with separate ANOVAs in order to compare my results with those of Kjellberg, Ljung and Hallman (2008) who found there was less of an effect of noise on recall of words in a list on those with higher working memory ability than there was on those with lower working memory capacity. Kjellberg et al. (2008) found that the recall of later words in a list, but not earlier words, was associated with working memory capacity. Participants with lower working memory scores remembered fewer words when they were presented in background noise, but the memory of those with higher working memory was less affected by the background noise. My results may differ from those of Kjellberg et al. (2008) because I used single words rather than lists. Furthermore, I assessed recognition memory rather than recall, and the mechanisms underlying the effects of working memory on recognition memory may be different than the effects on recall. However, this doesn't explain why there was no effect of listening condition or cognitive load (single- vs. dual-task) on word memory. There are several possible reasons for why no effects were found, including that the task, overall, was too difficult in all conditions. There may have been enough differences in the cognitive resources of participants to lead to differences in their performance on the primary and secondary tasks and listening effort, but the tasks may have taxed everyone enough that no resources were allocated to encoding the words. Again, this may have had an effect on motivation; audibility of the words may have been too low to allow sufficient encoding for memory. Participants may have been engaged in the task when the words were presented, but due to overall difficulty, they withdrew attention from the task immediately after responding. Conversely, the lack of differences in recognition memory may have nothing to do with the difficulty of the task, but may be a result of the experiment design. The words that were being tested were all ones that the participants had spoken aloud. The act of saying the words would lead to each word having an equally strong encoding event, providing a distinct memory for each of them. Due to this, memory for words in each of the conditions would be equated, producing no differences in recognition ability between conditions. In this case, all the words were equally well-remembered, regardless of listening condition, due to saying them out loud.

While working memory ability was not an indicator of recognition memory performance, it was correlated with other measures. Although reading and operation span scores were correlated, only reading span scores correlated with performance on other measures. For this reason, the following discussion relates to reading span scores as the measure of working memory capacity. People with higher working memory capacity had lower levels of error on the tracking task in the simulated hearing loss condition. This relationship is demonstrated by the negative correlations between reading span scores and average and standard deviation of tracking errors. This indicates that those with higher working memory capacity have greater ability to manage the demands of the dual-task conditions. Participants with lower working memory capacity were not as able to manage the demands of the dual-task conditions. This reduced ability was reflected in the higher level of error on the tracking task. The correlation between reading span scores and performance on the tracking task was only seen in the most difficult listening condition (hearing loss simulation). This suggests that while differences in working memory capacity can manifest as performance differences, the conditions need to be challenging in order to demonstrate the effect. Both high and low working memory capacity groups had similar performance levels in the easier conditions, but in the hardest condition, those with lower working memory capacity lacked sufficient resources to commit to the secondary task. There were no significant correlations between reading span scores and word recognition accuracy in any condition, indicating that the individual differences in working memory capacity manifest in the secondary task but not in the primary task. These results align with the ELU hypothesis that those with higher working memory capacity will exert less effort than those with lower working memory capacity when listening in challenging conditions.

These findings have implications beyond the lab. When someone is focused on listening in easy conditions, the effects of cognitive resources may be minimal. However, if someone is listening in more challenging conditions and engaged in more than one activity, the effects of cognitive resources may be more apparent. A real-world example of this is driving while talking to either a passenger or someone on the phone. Those with lower cognitive resources may experience detriments in driving performance when trying to focus on listening and conversation. Investigation of how motivation affects performance is a topic of interest for future research. If participants were motivated to focus on one task over the other (either listening or tracking), would I see maintenance of tracking performance at a cost to word recognition performance? In the present study, participants were not instructed to focus on either task, but the experiment setup likely informed them that the listening task was my task of interest. If they were instructed to prioritize tracking accuracy, then I would expect the differences in working memory capacity to be reflected in the word recognition performance, due to the switch in attentional and cognitive resources allocation.

The difference between high and low working memory capacity participants was also displayed in the correlation between the reading span scores and self-reported listening effort in the pink noise dual-task (tracking) condition. This correlation shows that participants with higher working memory capacity find listening in the pink noise condition while tracking to be less effortful than those with lower working memory capacity. Again, this relationship is only seen for one specific condition. Listening in pink noise is the easiest listening condition, yet it is in this one, while tracking, that the differences between high and low working memory participants become evident. There are two possible explanations for this correlation. The first is that this is the condition (low listening difficulty and high cognitive load difficulty) that separates the high from low working memory participants. This means that those with high working memory capacity found this condition to be easier than those with lower working memory capacity. Again, this would be due to them having more cognitive resources to apply to the tasks, therefore finding it easier to listen and understand the words even while tracking, which is what the ELU hypothesis predicts. The second explanation is that, despite listening effort following the expected pattern across listening conditions, it doesn't show differences across individual working memory in every condition. This may be due to it being a subjective measure of effort, where participants may not have an accurate idea of how effortful the task really is. Those with low working memory may rate listening as more effortful because they are allocating a lot of their resources to it. Those with higher working memory may rate a similarly difficult task as equally effortful because they have ample resources to apply to it and therefore have a sense of its difficulty, proportional to their available resources. Listening effort ratings, overall, may be difficult to interpret due to their subjective nature. This type of rating can, in future, be compared with physiological, and therefore objective, measures of effort. Such measures include using changes in pupil diameter and EEG power to not only measure effort objectively, but to also see how well subjective and objective measures agree.

My findings support the claim that many factors affect listening and listening effort. The division of resources between tasks, as well as individual differences in resource availability, interacts in a number of ways to influence listening. These tradeoffs and interactions require more study, but my findings provide an encouraging foundation for future investigations.

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Table 1
Mean average and standard deviation of tracking error measured in pixels; mean word recognition accuracy in proportion correct; and mean listening effort ratings (on a scale of 1-7). Standard deviations are shown in brackets.

		Pink Noise	Babble	Simulated Hearing Loss
Average Tracking Error		104.23	106.68	117.02
		(27.97)	(30.64)	(36.42)
Standard Deviation of Tracking Error		65.60	70.63	75.36
		(16.50)	(16.81)	(22.80)
Word Recognition				
	No Tracking	0.86	0.73	0.35
		(0.08)	(0.12)	(0.13)
	Tracking	0.88	0.78	0.35
		(0.07)	(0.10)	(0.12)
Listening Effort				
	No Tracking	3.10	4.22	5.89
		(1.39)	(1.04)	(0.99)
	Tracking	3.23	4.27	5.54
		(1.24)	(0.96)	(1.23)

Figure 1: Word recognition accuracy by condition.

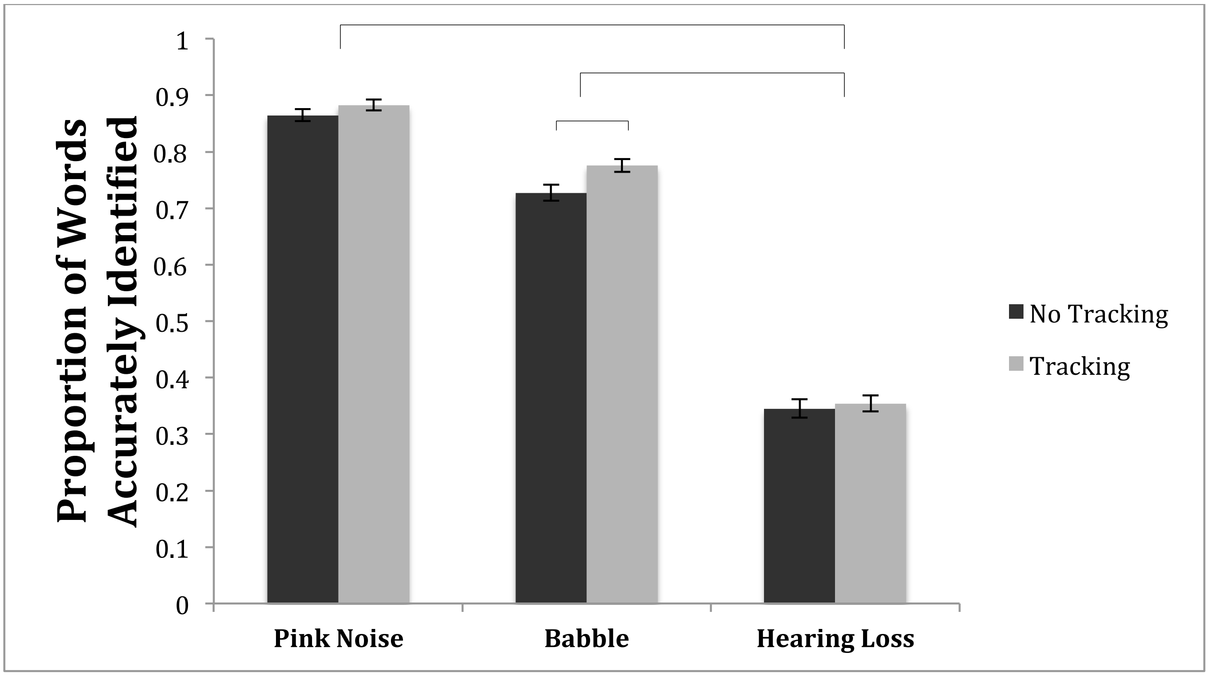


Figure 2: Subjective ratings of listening effort by condition.

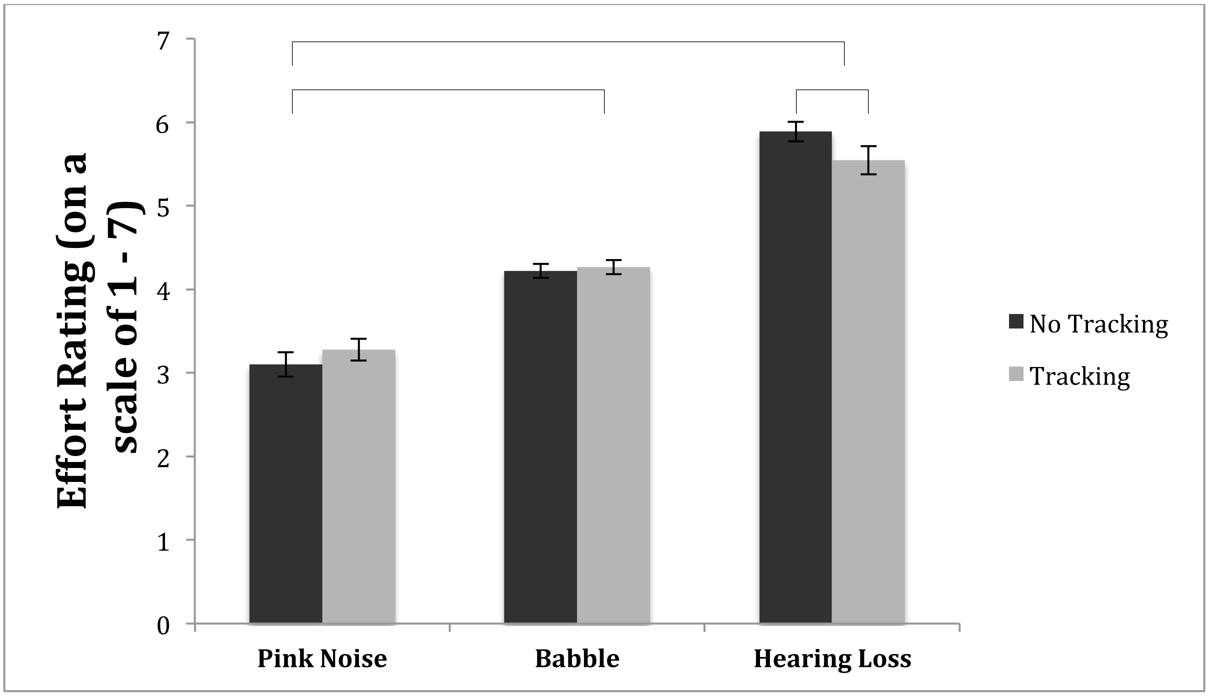


Figure 3: Tracking errors, separated by average and standard deviation of the tracking error, shown for each noise condition.

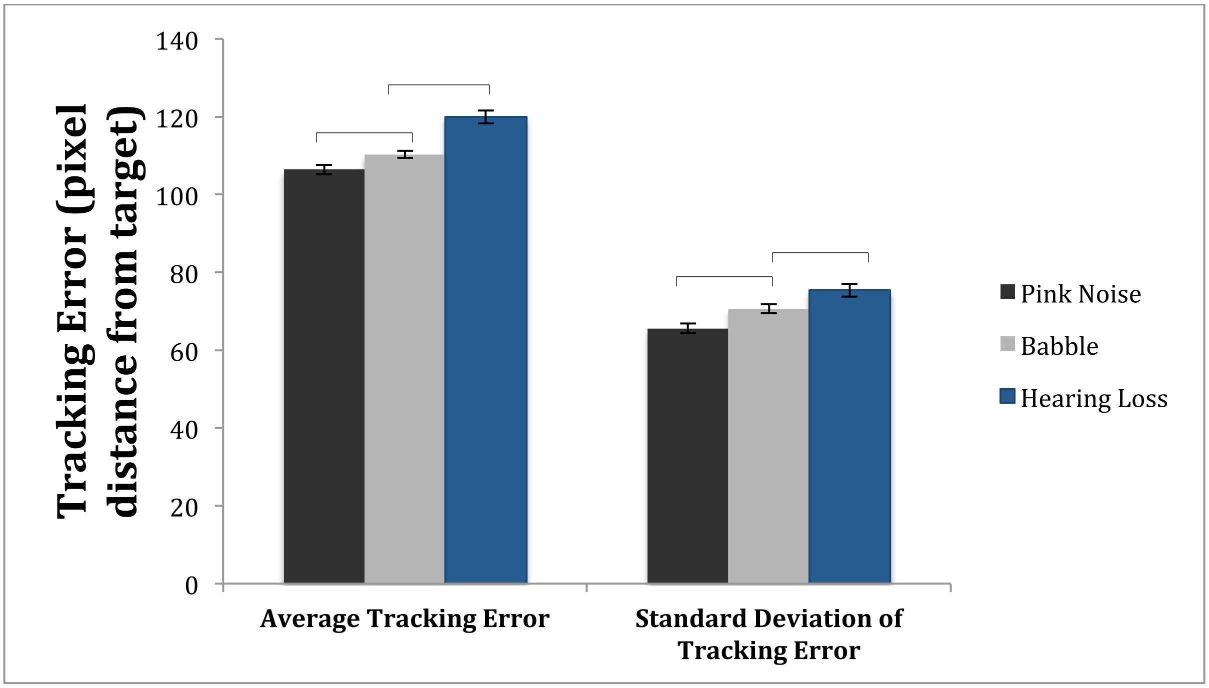


Figure 4: d' recognition memory accuracy scores by condition.

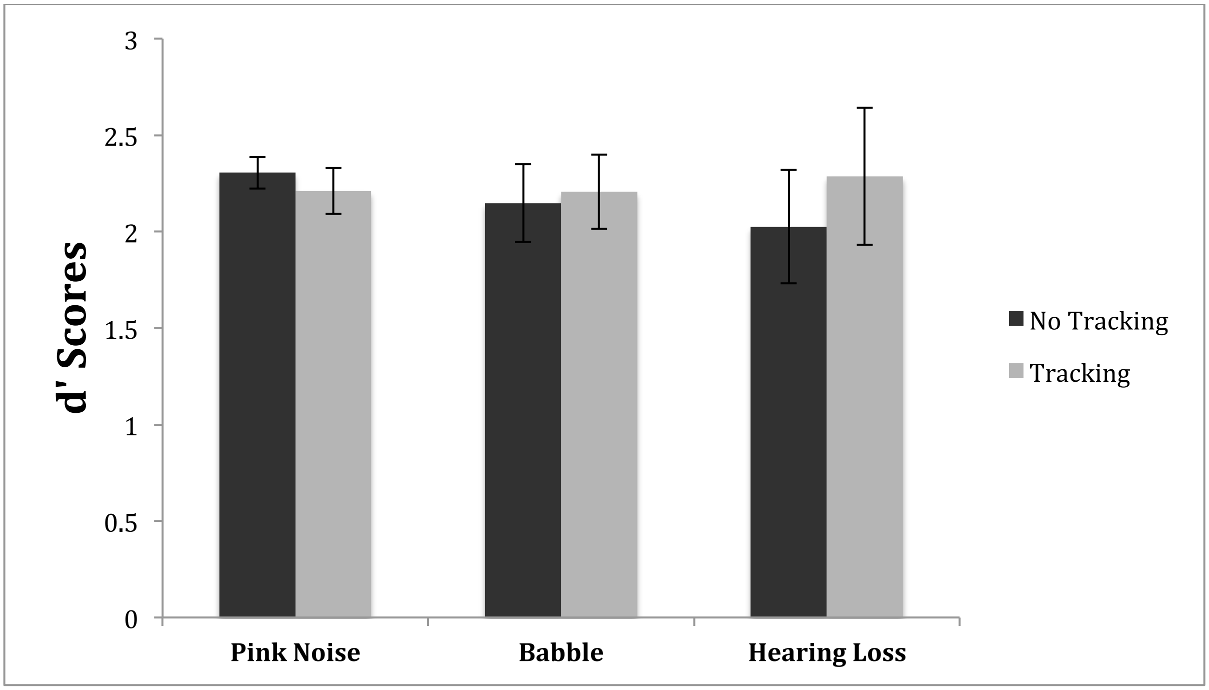


Figure 5: Average tracking error, measured in pixels, over the time-course of the trial, where 1 second is the onset of the stimulus.

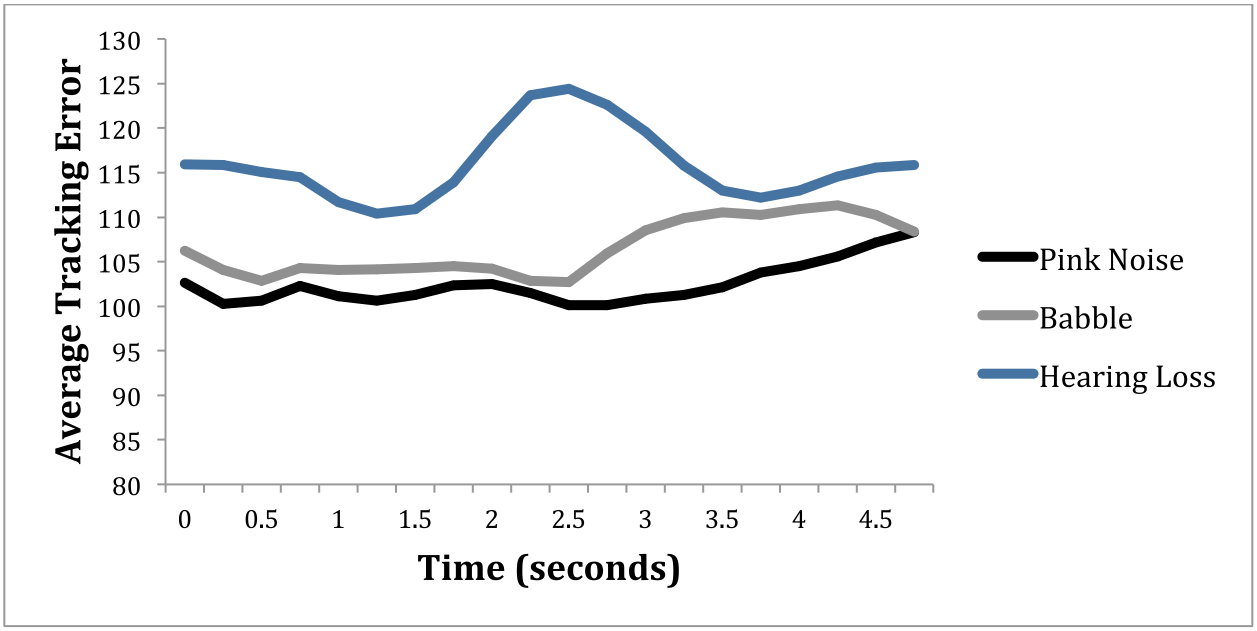


Figure 6: Standard deviation of tracking error, measured in pixels, over the time-course of the trial, where 1 second is the onset of the stimulus.

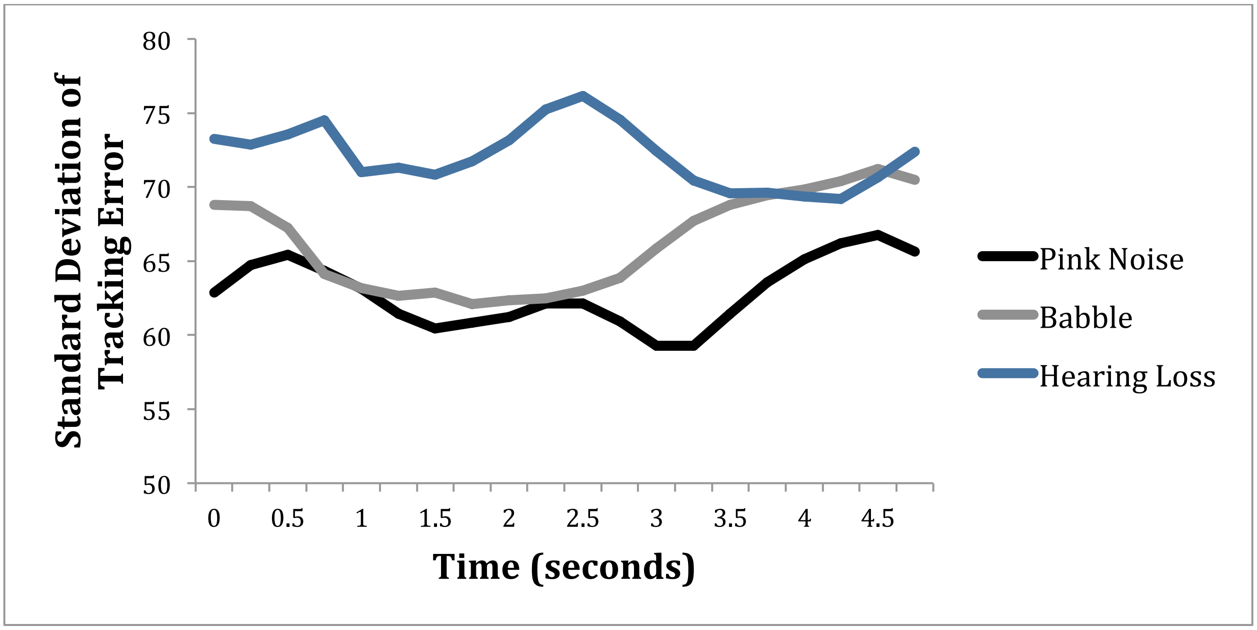


Figure 7: Correlation between R-Span and O-Span scores.

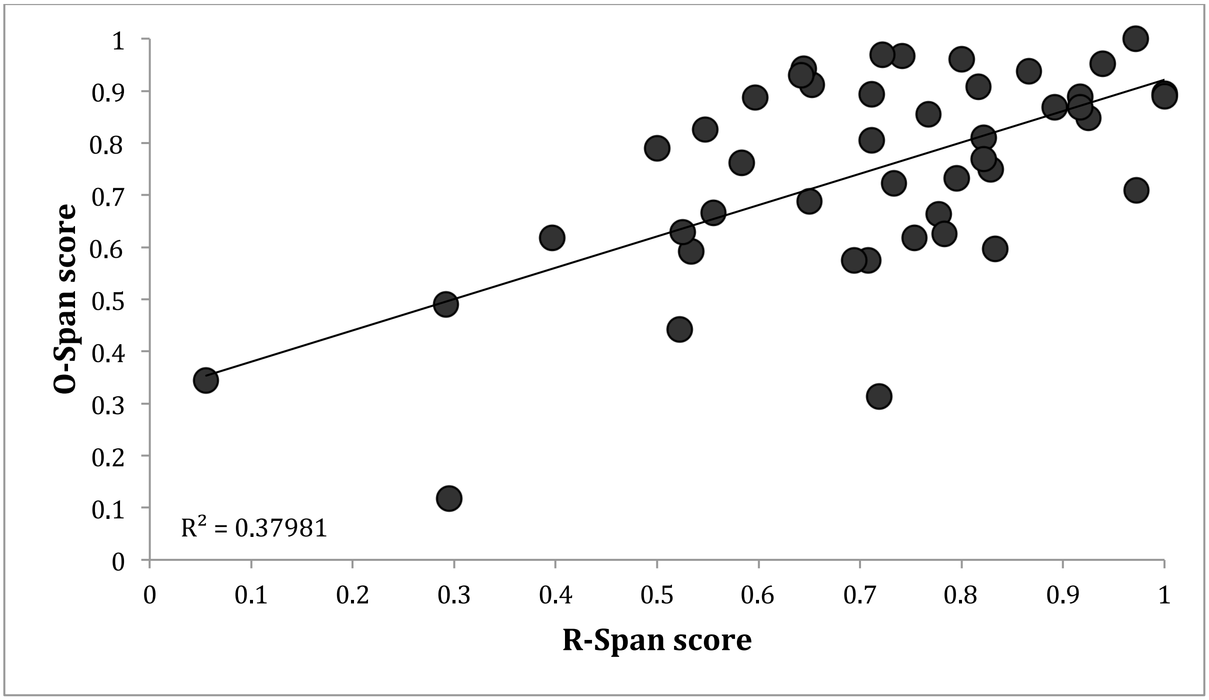


Figure 8: Correlation between R-Span working memory score and average tracking errors in the simulated hearing loss condition.

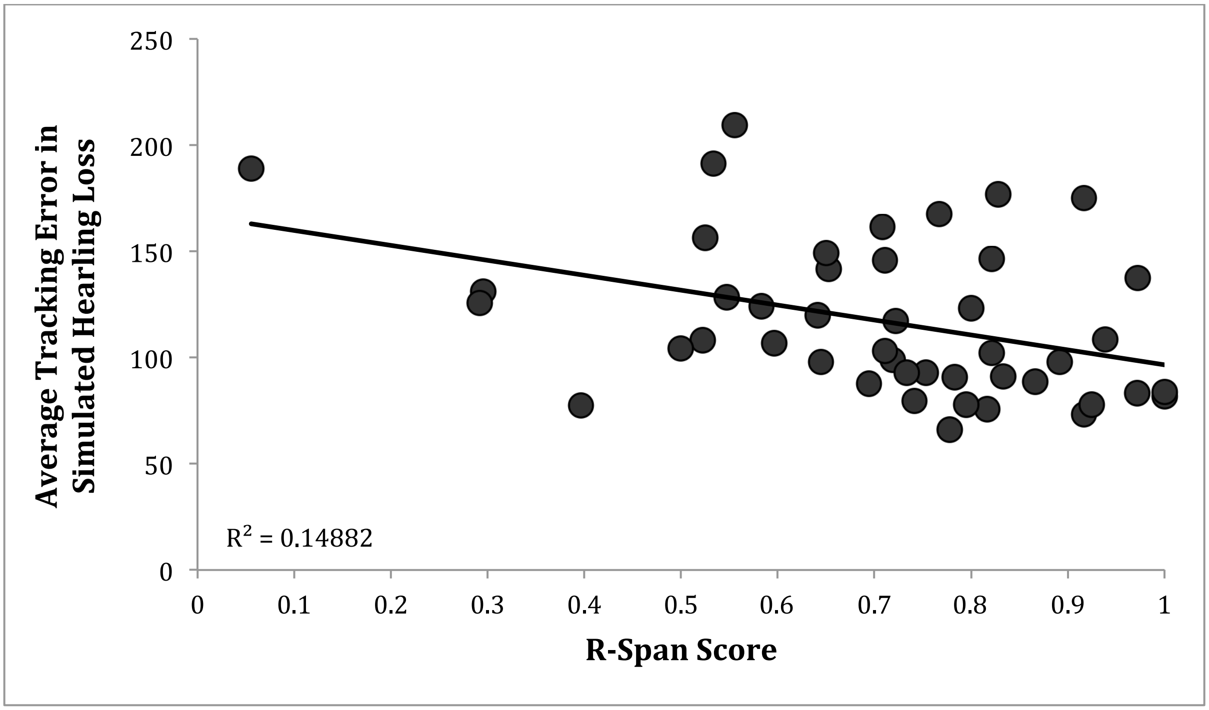


Figure 9: Correlation between R-Span working memory score and the standard deviation of the tracking error in the simulated hearing loss condition.

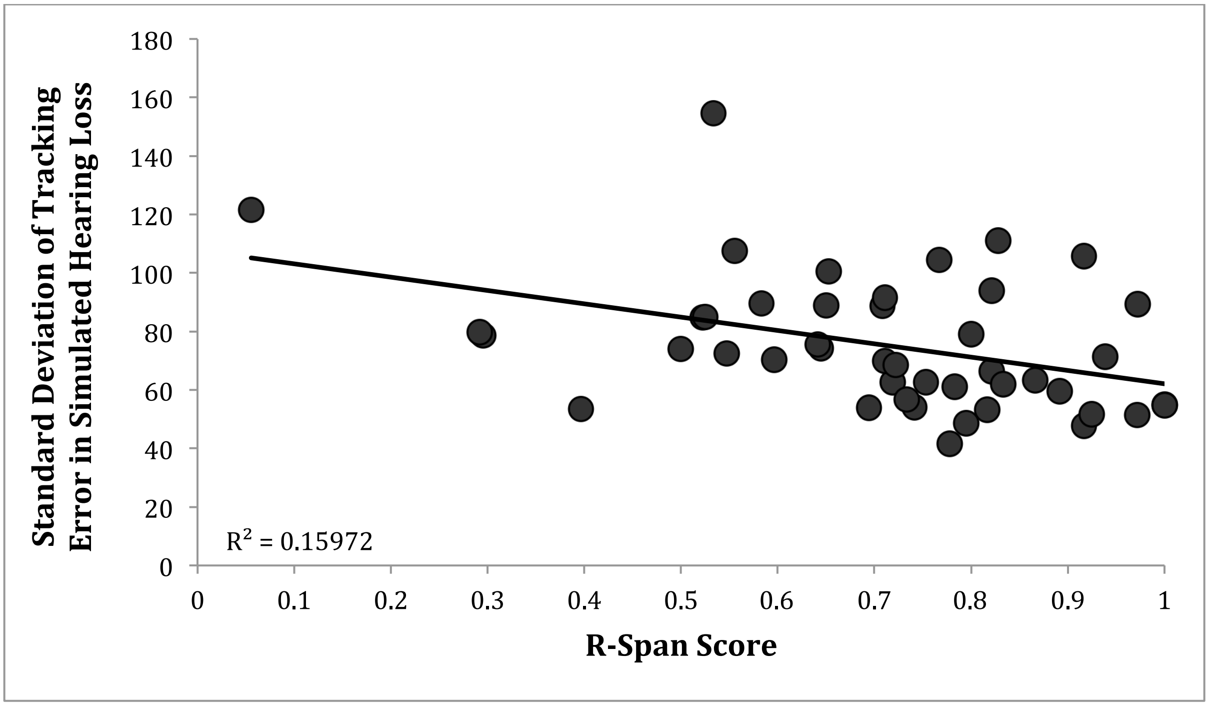
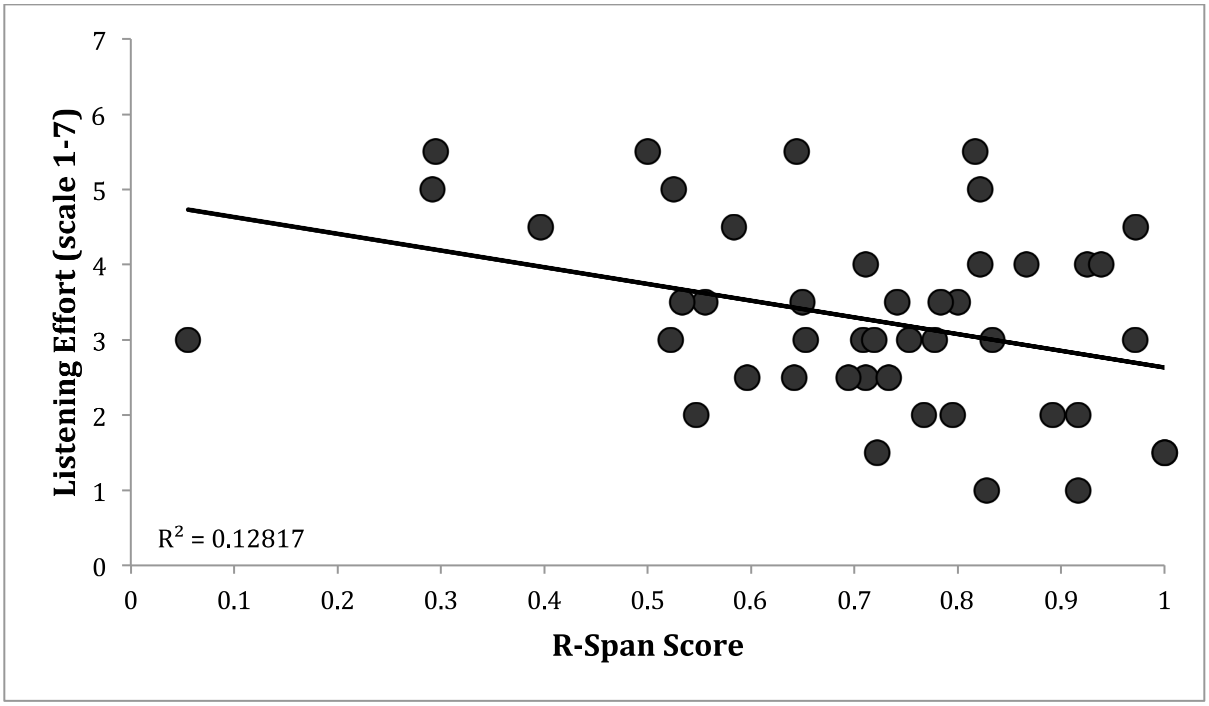


Figure 10: Correlation between R-Span working memory score and subjective ratings of listening effort in the tracking plus pink noise condition.



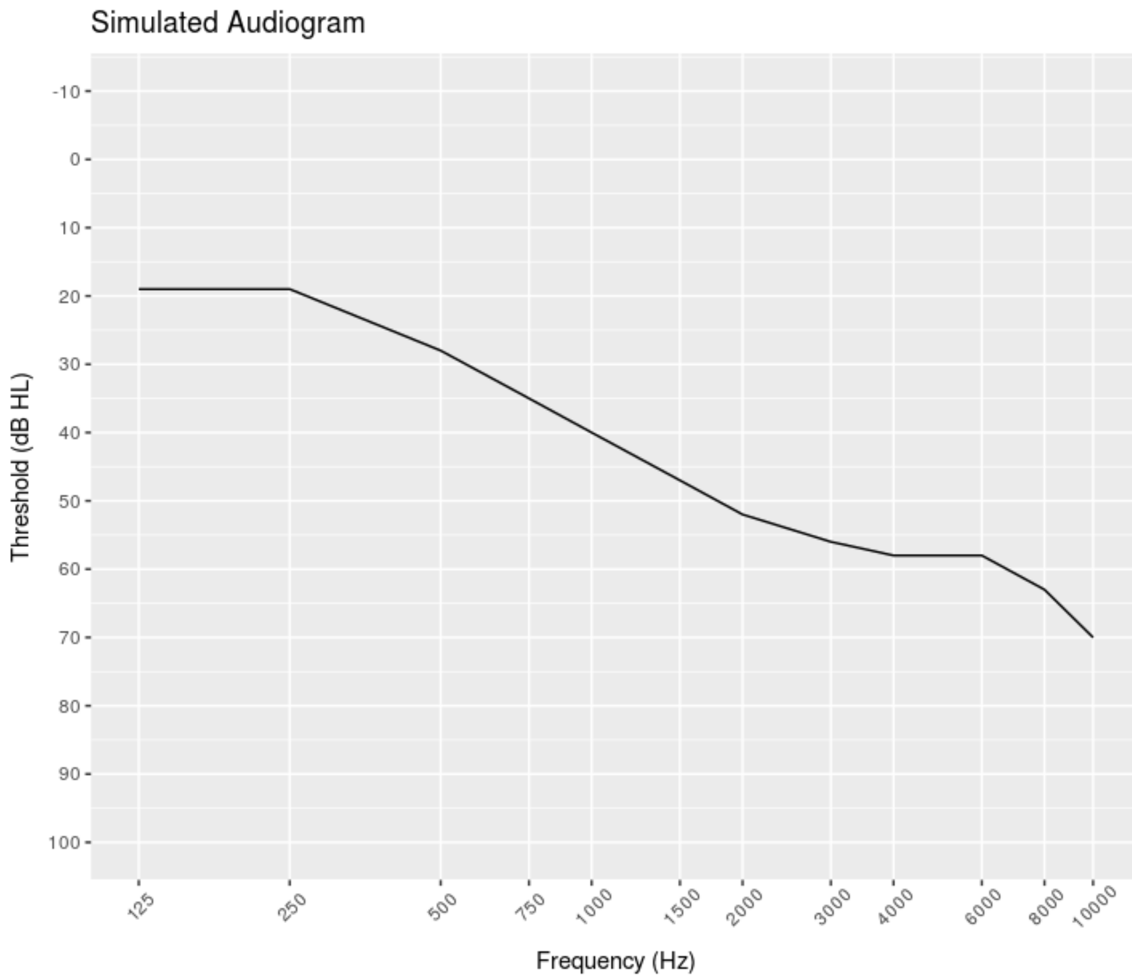
Appendix A

MATLAB function used to generate Pink Noise (Zhivomirov, 2013).

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   Pink Noise Generation with MATLAB Implementation    %
%                                                       %
% Author: M.Sc. Eng. Hristo Zhivomirov       07/30/13  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function y = pinknoise(N)

% function: y = pinknoise(N)
% N - number of samples to be returned in row vector
% y - row vector of pink (flicker) noise samples

% The function generates a sequence of pink (flicker) noise samples.
% Pink noise has equal energy in all octaves (or similar log bundles) of frequency.
% In terms of power at a constant bandwidth, pink noise falls off at 3 dB per octave.

% difine the length of the vector
% ensure that the M is even
if rem(N,2)
    M = N+1;
else
    M = N;
end

% generate white noise
x = randn(1, M);

% FFT
X = fft(x);

% prepare a vector for 1/f multiplication
NumUniquePts = M/2 + 1;
n = 1:NumUniquePts;
n = sqrt(n);

% multiplicate the left half of the spectrum so the power spectral density
% is proportional to the frequency by factor 1/f, i.e. the
% amplitudes are proportional to 1/sqrt(f)
X(1:NumUniquePts) = X(1:NumUniquePts)./n;

% prepare a right half of the spectrum - a copy of the left one,
% except the DC component and Nyquist frequency - they are unique
X(NumUniquePts+1:M) = real(X(M/2:-1:2)) -1i*imag(X(M/2:-1:2));

% IFFT
y = ifft(X);

% prepare output vector y
y = real(y(1, 1:N));

% ensure unity standard deviation and zero mean value
y = y - mean(y);
yrms = sqrt(mean(y.^2));
y = y/yrms;

end
```

Appendix B

Simulated audiogram of hearing loss.



Appendix C

Listening effort scale (as seen in Johnson, Xu, Cox and Pendergraft (2015)).

Listening Effort Scale

1. No effort
2. Very little effort
3. Little effort
4. Moderate effort
5. Considerable effort
6. Much effort
7. Extreme effort