# The Effects of Hearing Aid Use on Listening Effort and Mental Fatigue Associated With Sustained Speech Processing Demands

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**Objectives:** To maintain optimal understanding, persons with sensorineural hearing loss (SNHL) often report a need for increased attention, concentration, and "listening effort" compared with persons without hearing loss. It is generally assumed that this increased effort is related to subjective reports of mental fatigue in persons with hearing loss. Although the benefits of hearing aids for improving intelligibility are well documented, their impact on listening effort and mental fatigue are less clear. This study used subjective and objective measures to examine the effects of hearing aid use and advanced hearing aid features on listening effort and mental fatigue in adults with SNHL.

**Design:** Sixteen adults (aged 47–69 years) with mild to severe sloping SNHL participated. A dual-task paradigm assessed word recognition, word recall, and visual reaction times (RTs) to objectively quantify listening effort and fatigue. Mental fatigue was operationally defined as a decrement in performance over the duration of the experiment (approximately 1 hr). Participants were fitted with study hearing aids and tested unaided and in two aided conditions (omnidirectional and with directional processing and digital noise reduction active). Subjective ratings of listening effort experienced during the day and ratings of fatigue and attentiveness immediately before and after the dual-task were also obtained.

**Results:** Word recall was better and dual-task RTs were significantly faster in the aided compared with unaided conditions, suggesting a decrease in listening effort when listening aided. Word recognition and recall in unaided and aided conditions remained relatively stable over the duration of the dual-task, suggesting these processes were resistant to mental fatigue. In contrast, dual-task RTs systematically increased over the duration of the speech task when listening unaided, consistent with development of mental fatigue. However, dual-task RTs remained stable over time in both aided conditions suggesting that hearing aid use reduced susceptibility to mental fatigue. Subjective ratings of fatigue and attentiveness also increased significantly after completion of the dual-task; however, no differences between unaided and aided subjective ratings were observed. Correlation analyses between subjective and objective measures of listening effort and mental fatigue showed no strong or consistent relationship. Likewise, subject variables such as age and degree of hearing loss showed no strong or consistent relationship to either subjective or objective measures of listening effort or mental fatigue.

**Conclusions:** Results from subjective and select objective measures suggest sustained speech-processing demands can lead to mental fatigue in persons with hearing loss. It is important to note that the use of clinically fit hearing aids may reduce listening effort and susceptibility to mental fatigue associated with sustained speech-processing demands. The present study design did not reveal additional benefits, in terms of reduced listening effort or fatigue, from use of directional processing and digital noise-reduction algorithms. However, experimental design limitations suggest further work in this area is needed. Finally, subjective and objective measures of listening effort and mental fatigue due to sustained speech-processing demands, were not strongly associated, suggesting that these measures may assess different aspects of listening effort and mental fatigue.

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## INTRODUCTION

Hearing loss, like background noise and reverberation, can degrade speech understanding and lead to communication difficulties. To maintain optimal understanding, listeners with hearing loss must allocate more cognitive resources to speech processing than do listeners without hearing loss. This increase in cognitive resources required to understand degraded speech has been referred to as an increase in "listening effort" (Downs 1982; Hick & Tharpe 2002; McCoy et al. 2005). According to Capacity Theory of Attention cognitive resources are not infinite (e.g., Kahneman 1973; Baddeley 1986). Thus using additional cognitive resources to decode speech leaves fewer resources available for other tasks. For example, to maintain optimal understanding in a challenging situation, persons with hearing loss may need to shift more resources from other ongoing cognitive tasks (e.g., visual processing or memory rehearsal) than individuals without hearing loss, potentially impacting ease of communication (McCoy et al. 2005; Baldwin & Ash 2011; Picou et al. 2011).

Although increasing the allocation of cognitive resources dedicated to understanding speech may help optimize intelligibility, it may also have negative consequences. Specifically, research suggests the sustained cognitive effort required to offset auditory degradation due to hearing loss may lead to subjective reports of mental fatigue (Hétu et al. 1988; Ringdahl & Grimby 2000; Kramer et al. 2006; Nachtegaal et al. 2009). Following this reasoning we may also predict that factors, such as hearing aids, which improve speech understanding may also reduce listening effort and limit susceptibility to mental fatigue. This study tests this hypothesis directly.

Shifts in cognitive resource allocation (i.e., changes in listening effort) can be quantified using subjective, physiologic, and behavioral techniques (Zekveld et al. 2010; Mackersie & Cones 2011; Picou et al. 2011). A common behavioral method for quantifying listening effort in persons with hearing loss is the dual-task paradigm (Gosselin & Gagné 2010). Results from studies using dual-task paradigms, and other measures of cognitive processing, have clearly shown that hearing loss can lead to increased cognitive processing demands and listening effort when processing speech (Rabbitt 1991; Hällgren et al. 2005; McCoy et al. 2005; Zekveld et al. 2010).

There is also evidence suggesting that hearing aid use can reduce the cognitive resources needed to process speech and thus reduce listening effort, at least in some conditions (Downs 1982; Gatehouse & Gordon 1990; Hällgren et al. 2005; Picou et al. 2011). Downs (1982) used a dual-task paradigm combining word recognition (primary task) and visual reaction times (RTs; secondary task) to examine the effects of hearing aid use on listening effort. Results showed that word recognition and visual RTs improved when aided, suggesting that cognitive resources being used for processing unaided speech were freed when listening aided, allowing for faster visual RTs. Hällgren et al. (2005) also found hearing aid use reduced listening effort. However, benefit was observed only in quiet and when the speech task was cognitively challenging. Picou et al. (2013) used a dual-task paradigm similar to that of Downs (1982), and found that hearing aid use resulted in a small, but significant, reduction in listening effort that was modulated, in part, by working memory. Across studies, results suggest hearing aid use may reduce listening effort at least in some listening conditions.

In addition to benefits from simple hearing aid gain, there is some suggestion that signal processing features, such as directional processing and digital noise-reduction (DNR) algorithms, can reduce listening effort and thus potentially reduce mental fatigue (Sarampalis et al. 2009). In separate experiments using a memory task and a dual-task paradigm, Sarampalis et al. (2009) showed reduced cognitive processing demands with use of a simulated hearing aid DNR algorithm in normal hearing adults. However, similar work in people who have hearing loss and use actual hearing aids is lacking. This study also explores potential indirect benefits of directional processing and DNR use on listening effort and speech-processing–related mental fatigue.

Subjective data also support the hypothesis that hearing aid use, and DNR, can reduce listening effort (e.g., Humes et al. 1999; Hällgren et al. 2005; Noble & Gatehouse 2006; Bentler et al. 2008). For example, Noble and Gatehouse (2006) used the Speech Spatial and Qualities of Hearing Questionnaire (SSQ; Gatehouse & Noble 2004) to examine subjective benefits from unilateral and bilateral hearing aid fittings. They found bilateral hearing aid use significantly reduced subjective ratings of concentration, effort in listening, and distractibility compared with the unaided condition. Likewise, Bentler et al. (2008) showed subjective ratings of “ease of listening” significantly improved with DNR use even though measured intelligibility did not change. These objective and subjective results suggest hearing aid use and advanced signal processing features can reduce cognitive processing demands and thus listening effort. However, the effects of hearing aids and signal processing on subjective and objective measures of mental fatigue have not been studied.

## Listening Effort and Mental Fatigue

It is generally assumed that the increased listening effort observed in the laboratory is associated with subjective difficulties experienced by persons with hearing loss in everyday settings (e.g., Edwards 2007; Zekveld et al. 2010). In fact, anecdotal and self-reports of stress, tension, and fatigue resulting from hearing loss related communication difficulties are common (e.g., Copithorne 2006; Edwards 2007) and consistent with results from controlled laboratory and field studies. These studies have shown that deficits in auditory processing associated with hearing loss can lead to subjective reports of increased listening effort and have a significant negative impact on quality of life (Hétu et al. 1988; Kramer et al. 2006; Nachtegaal et al. 2009). For example, Hétu et al. (1988) found metal plant workers reported the need for increased attention, concentration, and effort to compensate for work-related hearing difficulties. A conclusion from interviews with these participants was that the additional mental effort exerted due to their hearing loss led to increases in stress, tension, and fatigue. A similar finding was reported by Kramer et al. (2006), who found that increased mental effort required at work resulted in workers with hearing loss taking more sick leave due to complaints of “mental distress” than workers without hearing loss doing the same or similar jobs.

The link between laboratory studies showing increased listening effort in persons with hearing loss and subjective reports of fatigue due to sustained listening demands in everyday settings is intuitive; however, the strength of this relationship is not clear. For example, one might increase listening effort in a challenging situation by shifting cognitive resources to the communication process. Once that situation ends, however, the resources could be shifted back to other tasks and the long-term impact could be minimal. In contrast, subjective reports suggest that feelings of fatigue result from listening demands that are sustained over an extended time frame (e.g., Hétu et al. 1988; Kramer et al. 2006). Thus the relationship between subjective reports of fatigue in everyday settings and short-term changes in allocation of cognitive resources observed during laboratory based dual-task paradigms remains unclear. In this study we begin to explore this area by examining the relationship between sustained speech-processing demands and mental fatigue.

## Defining and Quantifying Mental Fatigue

Fatigue is a complex, multidimensional construct that can occur in both the physical and mental domains. Our focus is solely on mental fatigue, thus in this article the term fatigue and mental fatigue are used interchangeably. Because of its multidimensional nature, definitions of fatigue vary (Leavitt & DeLuca 2010). Similar to the concept of listening effort, fatigue can be defined and quantified using subjective and objective methods. Mental fatigue has been defined subjectively as a feeling or mood state associated with a lack of, or decline in, focus, concentration, alertness or mental energy and efficiency (Kennedy 1988; Lieberman 2007; Boksem & Tops 2008). Mental fatigue can also be defined objectively as a decline in cognitive performance resulting from sustained, or prolonged, mental demands (Kennedy 1988; DeLuca 2005). Mentally fatigued adults show a decreased ability to maintain attention and concentration, slowed mental processing, and impaired decision making (van der Linden et al. 2003; Bryant et al. 2004; DeLuca 2005).

DeLuca (2005) notes that conceptualizing mental fatigue as a decrease in cognitive performance due to sustained mental effort has been common since the late 1800s. There is, however, no objective “gold standard” for measuring mental fatigue. Performance on any cognitive task could potentially be used as test measure; however, tasks requiring sustained cognitive effort have been shown to be particularly effective (DeLuca 2005; Leavitt & DeLuca 2010). Lieberman (2007) reported that vigilance tasks, which require sustained attention, were quite sensitive to experimental variables that increased and decreased mental fatigue. In general, vigilance tasks require participants to maintain attention for and respond to simple, infrequent, target events (e.g., a light flash or tone) while ignoring irrelevant stimuli. Fatigue is inferred when response speed slows, accuracy decreases or false alarms increase (Lieberman 2007; Basner & Dinges 2011). For example, Fine et al. (1994) found that a visual vigilance task was sensitive to the dose-dependent effects of a stimulant (caffeine) and sedative (diphenhydramine) known to modulate fatigue. Lieberman et al. (1987) reported similar sensitivity using an auditory vigilance task to assess the effects of caffeine on susceptibility to fatigue.

In summary, despite substantial anecdotal and subjective evidence linking hearing loss and fatigue, this relationship has received little research attention. A review of the literature found no studies using objective measures to examine the relationship between speech processing, hearing loss, and fatigue. Nor were studies using objective measures to examine the effects of hearing aid use on fatigue identified. Thus a primary goal of this study is to begin to fill these gaps by examining the impact of hearing aid use on listening effort and susceptibility to speech-processing related fatigue. A secondary aim is to examine whether routine activation of advanced signal processing algorithms during daily activities would reduce susceptibility to fatigue on cognitively demanding tasks completed at the end of the day.

## PARTICIPANTS AND METHODS

### Participants

Sixteen adults (8 males), 47 to 69 years of age (mean 65.8), were recruited from the clinical population seen in the audiology department at the Vanderbilt Bill Wilkerson Center, Nashville, Tennessee. Most reported no major health issues other than hearing loss. However, one participant (S15; see Table 1) reported Graves disease, which was controlled by medications, and another participant (S16) reported neuropathy in the feet and legs, which resulted in some balance issues. Although these conditions have the potential to impact fatigue, a visual analysis of the data showed performance that fell within the range of the other participants' performances. Therefore data from all participants were included in the analyses described later in this article. All participants had a history of bilateral, symmetric, mild to severe sensorineural hearing loss (air–bone gaps ≤ 10 dB) based on testing completed during previous audiological evaluations. Air conduction thresholds were reassessed at frequencies between 250 and 8000 Hz to confirm stable audiometric thresholds and are shown in Figure 1.

Participants answered demographic questions about their employment and activity levels during the day. We were interested in examining effort and fatigue in persons who were either employed or communicatively active based on self-report. In addition to employment status, participants were asked "What percentage of your day do you spend in activities inside or outside the home that involve auditory interactions (e.g., talking or listening) with others?" Twelve participants were employed full-time and reported being communicatively active approximately 65% of the time during their day (range 45–90%). Data from one participant (S2), employed in a university post office, were inadvertently not recorded. The remaining four participants were no longer employed but reported being communicatively active approximately 61% of the time during their day (range 30–80%). Twelve participants were current bilateral hearing aid users and four were nonusers. The median duration of hearing aid use among wearers was 1.5 years (range 1 month–10 years). Participants also completed the Mini-Mental State Examination (Folstein et al. 1975) to rule out the presence of significant cognitive dysfunction. The median score across participants was 30 (no errors) and ranged from 26 to 30. Scores ≤23 are suggestive of cognitive impairment. Select characteristics of individual study participants are shown in Table 1.

### Procedures

Study procedures were reviewed and approved by the Vanderbilt Institutional Review Board in compliance with the Office of Human Resource Protection requirements. Participants were compensated for their time on a per-session basis. Audiometric thresholds were obtained in a sound-treated booth; all other testing was completed in a 5.9 × 5.1 × 2.5 m reverberation chamber modified with acoustic blankets to create a moderately reverberant condition. The average RT60 (the time it takes for sound to decay by 60 dB once the source is turned off) in the test room was approximately 450 msec.

The study required four separate laboratory visits, an initial fitting and training session followed by three experimental test sessions (unaided, aided basic, and aided advanced,

**TABLE 1. Participant characteristics**

| Subject | Right PTA | Left PTA | Test SNR | Age (yrs) | Gender | Education Level | Has Own Hearing Aids? | Hearing Aid Use (mos) | MMSE | Employed? | Percentage of Days Listening |
|---|---|---|---|---|---|---|---|---|---|---|---|
| S1 | 31.7 | 35.0 | 8 | 68 | F | 16 | Yes | 18 | 29 | Y | 75 |
| S2 | 41.7 | 40.0 | 9 | 67 | M | 13 | Yes | 120 | 28 | Y | NR |
| S3 | 53.3 | 43.3 | 12 | 68 | M | 16 | Yes | 60 | 29 | N | 50 |
| S4 | 33.3 | 40.0 | 8 | 64 | F | 18 | No | NA | 30 | Y | 75 |
| S5 | 53.3 | 50.0 | 10 | 47 | M | NR | No | NA | 30 | Y | 80 |
| S6 | 38.3 | 35.0 | 9 | 69 | F | 20 | No | NA | 30 | Y | 75 |
| S7 | 36.7 | 38.3 | 9 | 68 | M | 16 | Yes | 24 | 30 | Y | 90 |
| S8 | 33.3 | 30.0 | 9 | 52 | F | 15 | Yes | 26 | 30 | Y | 75 |
| S9 | 56.7 | 55.0 | 8 | 57 | M | 23 | Yes | 1 | 29 | Y | 50 |
| S10 | 33.3 | 36.7 | 11 | 68 | M | 16 | Yes | 36 | 29 | Y | 50 |
| S11 | 31.7 | 33.3 | 4 | 69 | F | 15 | No | NA | 30 | N | 30 |
| S12 | 46.7 | 48.3 | 12 | 70 | F | 15 | Yes | 21.6 | 28 | N | 60 |
| S13 | 43.3 | 51.7 | 8 | 82 | F | 18 | Yes | 18 | 30 | N | 75 |
| S14 | 36.7 | 41.7 | 6 | 63 | M | 19 | Yes | 6 | 30 | Y | 45 |
| S15 | 46.7 | 45.0 | 8 | 58 | F | 18 | Yes | 12 | 30 | Y | 50 |
| S16 | 46.7 | 45.0 | 12 | 83 | M | 13 | Yes | 12 | 26 | N | 80 |

*PTA, pure-tone average; MMSE, Mini-Mental State Examination; NR, data not recorded.*

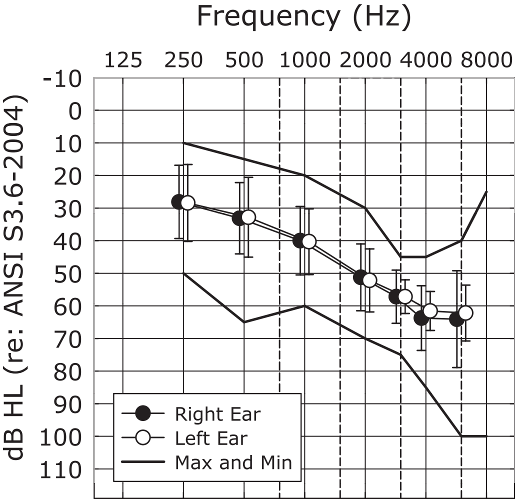

Fig. 1. Average audiograms of study participants with hearing loss. Open and filled symbols are for the left and right ears, respectively. Error bars = 1 SD. The maximum and minimum thresholds of test participants are shown by the solid lines.

details provided later in the article). The experimental sessions occurred on 3 separate days. Although the specific day and time varied based on scheduling needs, all participants were tested at the end of their "work day" (i.e., between 3 and 5 P.M.). At the end of a test session the hearing aid was reprogrammed for the next listening condition (basic or advanced) and a second 1- to 2-week acclimatization period began. Participants were instructed to wear their hearing aids daily during the acclimatization period. Participants were also asked to go one day without wearing the hearing aids and then come to the lab for unaided testing. Testing order was alternated such that half the participants were tested unaided first while the other half completed unaided testing last. Likewise, the order of aided testing alternated so that half started in the aided basic mode and the other half started in the aided advanced mode.

**Initial Session: Hearing Aid Fitting and Acclimatization** • During the first study visit, participants were fit with Phonak Micro Exelia BTE hearing aids using slim eartubes and dome ear tips. The aids were programmed in basic and advanced modes. In basic mode, the hearing aid microphone was omnidirectional and all advanced features, except for feedback management, were disabled, including directional processing and DNR. In advanced mode, the manufacturer's default settings for different listening environments were used. This included multichannel automatic directivity and algorithms designed to reduce reverberation, general background noise, and wind noise. Automatic directivity allowed the hearing aid microphone to switch between omnidirectional and multiple directional configurations depending on the background noise characteristics.

Directional and DNR function was verified in the laboratory (via front-back ratio measures and monitoring coupler output to a steady state noise with DNR off and on) before use with study participants. We did not monitor how often these advanced features were active while being used by participants. Thus it is possible that directional and DNR processing were not activated in some listening situations throughout the day, limiting their impact. However, program settings for these features were based on the manufacturer's recommendations and thus may be considered typical of fittings with this device. Before testing, matches to prescriptive targets for 65 dB SPL inputs (National Acoustics Laboratory-Nonlinear version 1; Dillon 1999) were verified in the real ear using an Audioscan VeriFit. In general, a good match to target was obtained in both ears (see Fig. 2). Mean deviations from target at 250 to 6000 Hz ranged from <1 dB to approximately 5 dB of (average root mean square deviation of 4.8 dB). After real ear testing hearing aid output in a 2-cc coupler was recorded and used for verification of hearing aid function at subsequent visits.

**Initial Session: Familiarization, Training, and Determination of Individual Test Signal-to-Noise Ratios** • To reduce learning effects that could potentially mask the development of fatigue, participants were familiarized and trained on study procedures before data collection sessions. All familiarization and training was done with the participants listening in the "aided advanced" condition. To familiarize participants with the speech materials each token was presented in quiet (55 dBA) along with an orthographic representation of the word shown on a 20 in computer monitor. Stimulus presentation was self-paced and words could be repeated as needed to ensure recognition. During this initial session participants also practiced on the experimental tasks (described later in this article). Practice sessions consisted of 15 to 30 trials on a given task and were completed in quiet and noise.

After familiarization, aided word recognition (advanced mode) in noise was assessed at multiple speech levels to estimate the signal to noise ratio (SNR) needed for approximately 70% correct aided recognition. The speech and background noise were the same stimuli as used in the experimental sessions. The speech stimuli were the 200 monosyllabic words from the Northwestern University Auditory Test #6, spoken by a female talker, from the Veterans Administration CD Version 1.1 (Stoppenbach et al. 1999). Digital copies of the 200 words and carrier phrases were randomized and concatenated into lists ranging from 8 to 12 words in length. Each word was separated by approximately 800 to 1000 msec of silence. Using all 200 words, four versions of 8, 9, 10, 11, and 12 word lists (20 lists

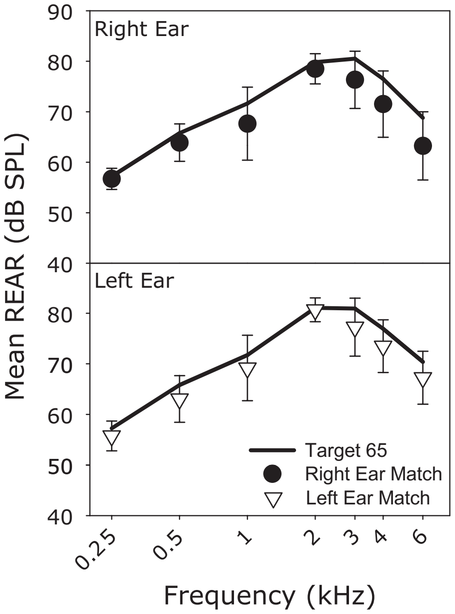

Fig. 2. Average, measured, and target REAR (in dB) for the right (circles) and left (triangles) ears. Error bars represent the root mean square deviation from target at each frequency. REAR, real ear aided response.

total) were created. This process was repeated six times to create a total of 120 unique lists for later playback (44 kHz sampling rate).

The background noise was a 30 sec segment of cafeteria babble spectrally shaped to match the long-term spectrum of the Northwestern University Auditory Test #6 words (without the carrier phrase). Five uncorrelated segments of cafeteria babble were presented from five loudspeakers surrounding the listener (1.2 m from the listener at azimuths of 60, 120, 180, 240, and 300°). The level of background noise from each loudspeaker was equated and then adjusted in unison to an overall level of 55 dBA, measured at the position of the listeners' head. The background noise was looped and run continuously during speech testing.

It should be noted that the background noise level chosen for this study (55 dBA) was not high enough to activate the devices' directional processing or noise-reduction algorithms. Thus regardless of the aid setting (basic or advanced), during the lab testing the hearing aids were functioning in omnidirectional mode with no DNR active. Our interest, however, was whether continuous access to advanced signal processing during daily activities would reduce cognitive processing demands and listening effort such that differences would be apparent when tested on our cognitively demanding dual-task completed at the end of the day.

To estimate the SNR needed for approximately 70% correct aided recognition a blocked procedure was used by first presenting 10 words at a +6 dB SNR. If the score at +6 dB SNR was better or worse than 70%, the SNR was adjusted up or down, in 1–4 dB steps. Performance was measured with additional 10-word lists at each SNR until the SNR needed for approximately 70% correct was identified. At least 30 words were presented at the test SNR to confirm it resulted in a score of approximately 70% correct. Test SNRs varied across participants from +4 to +12 dB (mean +9 dB). These individual SNRs were used during dual-task testing in the both aided and unaided listening conditions. We did not adjust the SNR in the unaided condition because we were interested in the impact of hearing aid use on listening effort and fatigue. Adjusting SNRs across conditions would confound that comparison.

**Experimental Sessions: Auditory Dual Task** • Previous research suggests that vigilance tasks are sensitive to changes in mental effort that can lead to mental fatigue (Lieberman 2007). We used a dual-task paradigm to assess vigilance and fatigue by monitoring changes in auditory word recognition, auditory serial recall, and visual RTs over time. The primary task was the word recognition component of the paradigm. Two secondary tasks (memory recall and visual RTs) were incorporated in an attempt to increase task sensitivity to fatigue. Previous work has shown that mental fatigue may increase with task complexity (van der Linden et al. 2003; Smit et al. 2004). The task was a modification of a serial recall task used by McCoy et al. (2005). The recall task used by McCoy et al. provided a measure of listening effort that was sensitive to subtle differences in hearing loss between their study groups. Present study participants listened to speech (0° azimuth; 1.2 m from the listener) and surrounding background noise. The background noise level was fixed (55 dBA) and speech levels were chosen individually such that average performance in the aided advanced condition was approximately 70% correct.

The speech stimuli consisted of strings of 8 to 12 words that varied randomly in length. Each word in the string was preceded by the carrier phrase "Say the word…" To allow the research assistant to monitor responses, participants wore a directional lavaliere microphone and repeated each word aloud immediately after presentation. The research assistant monitored the microphone input, scored responses, and recorded incorrectly repeated words. Participants were encouraged to guess if needed. In addition, to test our hypothesis that when sustained, cognitively challenging speech processing can lead to fatigue, participants were asked to hold the five most recent words in memory for later recall. The requirement to maintain five items in memory is possible, but challenging, particularly in difficult listening situations (e.g., Surprenant 2007). Finally, participants remained vigilant for a visual cue to be presented on a 20" widescreen computer monitor located on the floor directly in front of the speech loudspeaker, and were asked to press a button as quickly as possible once the visual marker appeared. The visual marker was the word STOP (48 font size) presented on a red background.

After responding to the visual marker participants repeated back, in any order, the final five words from memory. Because the word strings varied randomly in length participants were required to continually update the final five words being held in memory. If a word was incorrectly identified during the initial presentation then recall was only scored correct if that same word was later recalled. This method increased the total number of items available for scoring compared with basing recall scores on only those words that were correctly identified. In addition, word recall scores are highly correlated across scoring methods (i.e., only correctly identified words or any stated word), suggesting the impact of scoring method may be small (Kjellberg et al. 2008).

Immediately after recalling the words, participants pressed a button to start the next word string. This process continued, without breaks, for approximately 50 to 60 min, depending on the time required to complete the recall task and initiate the next trial. Stimulus presentation and RT measures were controlled and measured via custom-built software using E-Prime 2.0 (Psychology Software Tools, Pittsburgh, PA). Examining performance changes over time (i.e., recognition, recall, and RTs) provides an objective measure of fatigue (DeLuca 2005) which, in this case, is associated with sustained speech-processing demands.

**Experimental Sessions: Single-Task Visual RT Assessment** • To control for variations in motor function, which could increase variability on our dual-task, we obtained RTs to the visual stimulus alone before the start of the dual-task paradigm. This "single-task visual RT" measure mimicked the dual-task paradigm in that participants listened at the same levels of speech and noise and in the same room configuration as during dual-task testing. However, participants were instructed to ignore the speech and noise (i.e., not to repeat or try to recall any words) and focus solely on responding as quickly as possible to the visual prompt. RTs were displayed on the computer monitor after each trial and text was displayed to encourage participants to beat their time on the next trial. Participants completed 20 trials in each condition (unaided, aided basic, and aided advanced) immediately before dual-task testing in that condition. The median RT over those trials was taken as the single-task visual RT for that condition.

**Experimental Sessions: Subjective Ratings** • Before completing the single- and dual-task paradigms participants completed a five-item subjective rating scale. Three of the questions on the scale were adapted from the SSQ (Qualities of Hearing questions #14, 18, and 19) and assessed concentration, listening effort, and distractibility. The SSQ is reliable (Singh & Pichora-Fuller 2010) and sensitive to factors affecting listening effort (Noble & Gatehouse 2006). We were interested in how hearing aid use impacted concentration, listening effort, and distractibility for a participant on their test day. Therefore SSQ questions were modified such that ratings were based on experiences on the day of testing alone. For example, the question "Do you have to put in a lot of effort to hear what is being said in conversation with others?" was modified to read "*Did* you have to put in a lot of effort to hear what was being said in conversation with others *today*?" Second, the direction of the rating scale was reversed, compared with the original SSQ, so that 0 always reflected no or minimum difficulty and 10 reflected maximum difficulty. Participants then responded to each question by circling a number between 0 and 10. These responses provided a subjective measure of listening effort due to routine daily activities.

The final two questions, developed specifically for this study, were semantically similar to items on other validated fatigue scales (e.g., Multidimensional Fatigue Symptom Inventory; Stein et al. 1998). The questions were structured to mimic the format of the other questions; however, participants rated their current level of attention ("How well can you maintain your focus and attention *right* now?") and fatigue ("How mentally/physically drained are you *right* now?"). These questions were administered both before and after the dual-task and provided a subjective estimate of change in attention and fatigue due to completion of the study task.

## ANALYSIS

Of primary interest in this study was the impact of hearing aids, and use of advanced signal processing (directional and DNR), on listening effort and fatigue. To examine effects on listening effort we evaluated differences in word recognition, recall, and RTs between hearing aid conditions (unaided, aided basic, and aided advanced). Differences between hearing aid conditions were examined using repeated measures analysis of variance (ANOVA). Recognition, recall, and RT data were analyzed separately. The independent variables were hearing aid conditions and dependent variables were word recognition, word recall, or visual RT. Word recognition and recall scores, in percent correct, were converted to rationalized arcsine units before statistical analysis to stabilize error variance (Studebaker 1985). A 0.05 level of significance was used in all ANOVA analyses. In cases where the ANOVA assumption of sphericity was violated, a Greenhouse-Geisser correction was used to determine significance of test results.

Significant differences in unaided and aided word recognition ability would suggest that differences in listening effort, as measured via secondary task performance (word recall and visual RTs) should be apparent between conditions. Main effects of hearing aid condition from the ANOVA analyses (i.e., performance collapsed across block/time) were used to explore differences in listening effort between hearing aid conditions. Main effects of block/time (i.e., performance collapsed across listening conditions) from the ANOVA analyses were used to determine whether task performance changed over time. Trend analysis was used to assess whether performance, in a given hearing aid condition, varied in a systematic way over time. Decrements in performance over time on any test measure (recognition, recall, or RTs) would provide objective evidence of development of mental fatigue in that condition.

To analyze performance over time, data in each hearing aid condition were grouped into six, sequential, 200-word blocks (20-word lists). Each block of 200 words provided an average word recognition score, an average recall score, and a median visual RT. The word recall score was the average number of words correctly recalled, based on the last five words presented in each word list. Thus a participant's average recall score was based on 100 words (5 Words/String × 20 Strings). Visual RTs for each block were the median of 20 RT measures (1 RT/List × 20 Lists).

In addition to objective data derived from our speech-processing task, subjective estimates of listening effort and fatigue were also collected. Given the rank-based nature of the subjective ratings, differences between hearing aid conditions were examined using the Friedman test. Finally, relationships between subjective and objective measures of listening effort and fatigue, and between these measures and subject factors (i.e., age and degree of hearing loss), were explored using a Spearman's rank order correlation analysis including Bonferroni adjustments for multiple comparisons.

## RESULTS

### Objective Measures of Listening Effort and Fatigue

**Effect of Hearing Aid Use on Listening Effort** • Word recognition scores were analyzed first to confirm that hearing aid use improved word recognition thus, potentially, reducing listening effort. When averaged across all time blocks, results from an initial ANOVA analysis revealed a significant main effect of hearing aid condition ($F_{2,30} = 18.3$; $p < 0.001$). Follow-up planned comparisons revealed significantly poorer unaided (~63%), compared with aided basic ($F_{1,15} = 14.7$; $p = 0.002$) and aided advanced ($F_{1,15} = 29.5$; $p < 0.001$), word recognition (see mean data in Fig. 3). However, there was no difference between aided basic and advanced (both ~75%) recognition ($F_{1,15} = 1.98$; $p = 0.18$) suggesting activation of the advanced features during the day had a minimal effect on word recognition at the end of the day. Aided performance of ~75%, rather than the target 70%, suggests a practice effect despite our substantial training.

Differences in word recognition ability between unaided and aided conditions suggest that listening effort may have varied across conditions. Comparisons of secondary task performance (word recall and visual RTs) were used to assess differences in listening effort. Analysis of word recall data (averaged across serial position), again using a repeated measures ANOVA, revealed a similar pattern to the recognition data. Unaided recall (~57%) was poorer than recall in aided basic (~61%) or aided advanced (~63%) modes, suggesting reduced listening effort in the aided conditions (see mean data in Fig. 4). The difference between hearing aid conditions, although small, was significant ($F_{2,30} = 6.8$; $p = 0.004$). Follow-up planned comparisons using a series of single-factor ANOVAs revealed significantly poorer word recall in the unaided, compared with aided basic ($F_{1,15} =$

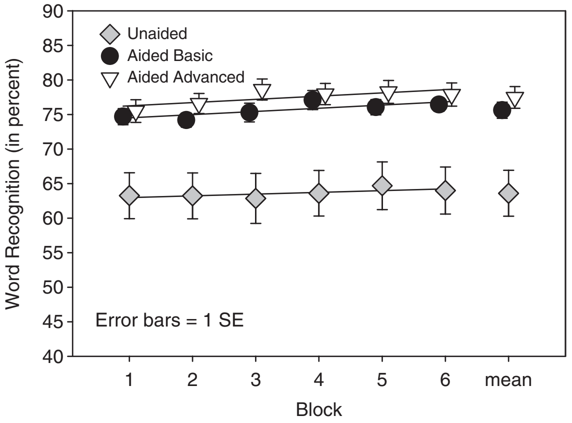

Fig. 3. Mean word recognition as a function of listening condition (unaided, aided basic, and aided advanced) and block/time. Error bars = 1 SE. The time from the start of block one to the end of block six is approximately 50 to 60 min. Solid lines show a best fit linear regression. "Mean" data show word recognition, averaged across all blocks, for each listening condition.

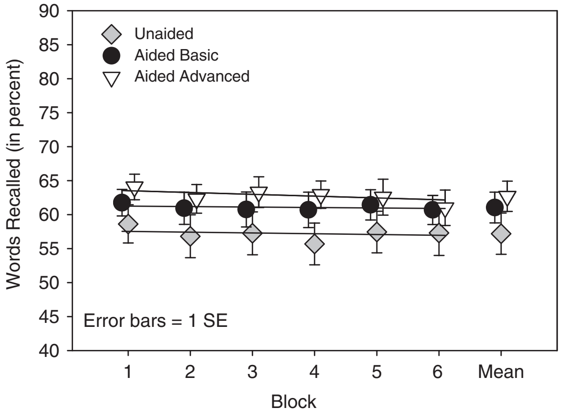

Fig. 4. Unaided and aided word recall, averaged across serial position, as a function of block/time. Error bars show 1 SE. Solid lines show a best fit linear regression to the average data. "Mean" data show word recall, averaged across all blocks, for each listening condition.

5.95; $p = 0.028$) or advanced ($F_{1,15} = 9.08$; $p = 0.009$), condition. There was no difference in word recall between the two aided conditions ($F_{1,15} = 2.38$; $p = 0.144$), suggesting similarities in listening effort in these conditions.

Measures of RTs obtained during dual-task testing provide an additional metric to assess listening effort across hearing aid conditions. Variability in absolute RTs among participants was large and related, in part, to differences in motor function/dexterity. To reduce variability in our dual task associated with motor function differences in RTs a "percent change" score was calculated for each participant as follows: Percent change = 100 × ([dual-task RT − single-task RT]/single-task RT). The percent change score provides a normalized measure of the change in RTs due to the addition of the speech recognition and recall demands. Positive values indicate RTs in the dual task were longer than single-task RTs. Because of technical difficulties and scheduling errors single-task RTs were not obtained from the first 2 participants, thus these analyses are based on results from 14 participants.

The initial repeated measures ANOVA explored differences in percent change scores between hearing aid conditions and over time (block). ANOVA results revealed a significant main effect of hearing aid condition ($F_{2,26} = 4.1$; $p = 0.05$) and block ($F_{5,65} = 4.8$; $p = 0.018$). The main effect of block, important in our assessment of fatigue, is discussed in the next section. Follow-up planned comparisons of the main effect of hearing aid condition showed that unaided RTs increased more from baseline levels ($F_{1,13} = 6.3$; $p = 0.03$) than RTs in the aided advanced, but not the aided basic ($F_{1,13} = 2.7$; $p = 0.12$), condition. In addition, the difference between the aided conditions was not significant ($F_{1,13} = 2.1$; $p = 0.17$; see mean data in Fig. 5).

**Effect of Hearing Aid Use on Fatigue** • Of specific interest in this study was how variations in listening effort resulting from hearing aid use may impact fatigue, quantified objectively as a performance decrement over time. Results, as described earlier, from the ANOVA analyses related to the main effect of block (time), and interactions between block and hearing aid condition, were used to explore fatigue effects. The initial ANOVA on word recognition scores revealed a significant main effect of block ($F_{5,75} = 4.18$; $p = 0.002$) suggesting word recognition varied over the duration of testing. However, in contrast to our initial hypotheses, rather than decreasing over time, trend analysis revealed a significant ($F_{1,15} = 9.8$; $p = 0.007$) linear trend of increasing word recognition over time. Comparing performance in the initial and final blocks of the dual task showed word recognition scores improved slightly (~1–2 percentage points) over time. However, the interaction between listening condition and block was not significant ($F_{10,150} = 1.36$; $p = 0.205$), suggesting word recognition improved in a similar manner across all conditions (see Fig. 3).

The initial ANOVA on word recall data (described earlier) showed, despite apparent differences in listening effort, no evidence of fatigue. Specifically, the main effect of block was not significant ($F_{5,75} = 0.98$; $p = 0.44$). Nor was the interaction between block and hearing aid condition significant ($F_{10,150} = 0.37$; $p = 0.95$), suggesting word recall performance was stable throughout testing in unaided and aided conditions (see Fig. 4). Additional analyses, exploring changes in word recall performance over time as a function of serial position of the recalled words supported these findings.

In contrast, the initial ANOVA on dual-task RTs (percent change data) revealed a significant main effect of block ($F_{5,65}$ =

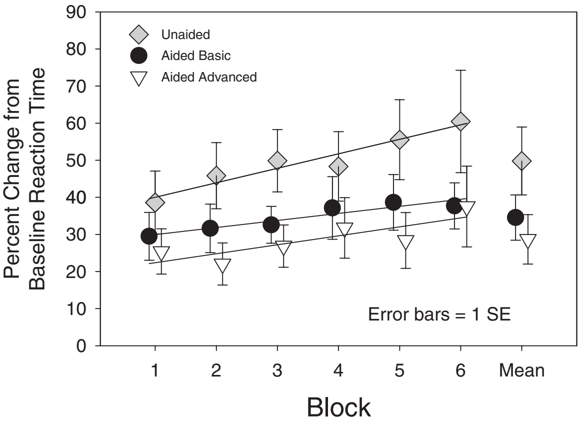

Fig. 5. Percent change from baseline reaction time as a function of block/time for each listening condition. Error bars = 1 SE. Solid lines show a best fit linear regression. "Mean" data show normalized RTs, averaged across all blocks, for each listening condition.

4.8; $p = 0.001$). Specifically, averaged across hearing aid conditions, RTs to the visual probe systematically increased over time during the dual-task, suggesting a systematic shift in cognitive resources from the visual RT task. Although the interaction between hearing aid condition and block was not significant ($F_{10,130} = 0.67$; $p = 0.75$), a primary focus of this study was to explore the impact of hearing aid use on the development of mental fatigue. Therefore, follow-up analyses using a series of single-factor repeated measure ANOVAs were conducted to examine changes in dual-task RTs, over time, in each hearing aid condition. Results revealed a significant effect of block only in the unaided condition ($F_{5,65} = 2.5$; $p = 0.036$). Trend analysis revealed that dual-task RTs increased significantly over time when listening unaided ($F_{1,13} = 5.36$; $p = 0.038$). The effect of block was not significant in the aided basic ($F_{5,65} = 1.4$; $p = 0.24$) or aided advanced ($F_{5,65} = 1.9$; $p = 0.11$) conditions (see Fig. 5).

## Subjective Measures of Listening Effort and Fatigue

In addition to the objective data described earlier, subjective estimates of listening effort and fatigue were also collected. Differences in mean subjective ratings of concentration, listening effort, and distractibility experienced during daily activities when listening unaided and aided were explored using a Friedman's test. These ratings provide an estimate of the cognitive load experienced by participants due to their daily routines (see Table 2). Despite apparent differences in some conditions, results revealed no significant difference between unaided and aided listening for any test question.

In addition to ratings of cognitive load during the day, estimates of mental fatigue and the ability to focus/maintain attention immediately before and after dual-task testing were also obtained. The post-task ratings provided an estimate of the subjective consequences of the dual task on mental/physical fatigue and attention. Differences between pre– and post–dual-task ratings of mental fatigue and attention were examined using the Friedman test. Results revealed a significant increase in subjective reports of fatigue and difficulty in maintaining attention/focus in all listening conditions after completion of the dual-task. The chi-square was ≥14 (2; n = 16; $p < 0.0001$) in all conditions. However, variability was large and the increase in subjective ratings was similar across all hearing aid conditions (see Table 3).

## Relationships Between Objective and Subjective Measures of Fatigue

Results based on both subjective and objective measures suggest our study task induced fatigue. A nonparametric correlational approach (Spearman's rho) was used to explore relationships between our subjective and objective measures of fatigue. First, relationships between objective measures of fatigue and (1) subjective ratings of concentration, effort, and distractibility experienced during the day and (2) present ratings of fatigue and attention obtained immediately before vigilance testing, were explored. Of interest was whether these subjective ratings, which were based on the participants' experiences during the day, were predictive of susceptibility to objectively measured speech-processing–related fatigue as measured in the laboratory at the end of the day. In addition, we examined whether changes in subjective ratings of fatigue and attention due to completion of our sustained speech task were related to our objective measures of fatigue (i.e., changes in word recognition, recall, and RTs).

**TABLE 2. Mean subjective ratings of concentration, listening effort, and distractibility experienced during daily activities when listening unaided and aided**

| Condition | Concentration | Effort | Distractability |
|---|---|---|---|
| Unaided | 5.3 (2.8) | 4.6 (3.1) | 3.4 (2.9) |
| Aided Basic | 3.9 (2.5) | 2.9 (2.3) | 4.6 (2.4) |
| Aided Advanced | 3.5 (2.6) | 3.1 (2.3) | 3.3 (3.0) |

*Values in parentheses represent 1 standard deviation.*

To objectively quantify fatigue a difference score was calculated by averaging performance over the last three blocks of our dual-task and subtracting that value from the average performance based on the first three blocks. Difference scores for word recognition, word recall, and visual RTs were calculated separately. The significance of correlations between a given subjective rating and our three objective measures of fatigue (changes in word recognition, recall, and dual-task RTs) were evaluated using a Bonferroni-adjusted alpha level of 0.0167 per test (0.05/3). Again, using this alpha level none of the comparisons examined were significant.

## Individual Variability in Speech Processing Related Fatigue

Although the sustained cognitive demands of our speech task were challenging, fatigue effects varied widely across participants. This variability is highlighted in Figure 6, which shows changes in individual, and mean, unaided dual-task RTs over the course of testing. Individual fatigue effects also varied substantially in the aided conditions. However, as suggested by the mean data in Figure 5, the general trend was for fewer participants to show substantial increases in dual-task RTs over the course of testing when aided. Correlational analyses were used to investigate factors responsible for this variability. Specific subject factors evaluated included: single-task visual RTs, pure-tone average (average hearing loss at 0.5, 1, and 2 kHz), high-frequency pure-tone average (average hearing loss at 2, 3, and 4 kHz), age, unaided word recognition ability (averaged across blocks), SNR used during testing, and self-rated percentage of time communicatively active. Relationships between these factors and (1) subjective (changes in subjective ratings of mental fatigue and focus/attention) and (2) objective (changes in word recognition, recall, and RTs) measures of mental fatigue were evaluated. Significance was assessed using a Bonferroni-adjusted alpha level of 0.0071 per test (0.05/7). Again, none of the comparisons remained significant following Bonferonni correction.

Employment status (working or retired) and hearing aid experience (user or not) are two additional factors that varied between participants and might be expected to influence effort and fatigue throughout the day. Unfortunately, the relatively small sample size and the unbalanced groups (e.g., only 4 of 16 participants were nonusers) in the study would make a statistical analysis of this question suspect. However, visual inspection of the data suggests that subjective and objective measures of fatigue were similar between the groups. For example, changes in unaided RTs over the course of testing, an objective measure of fatigue, for the four nonworking participants fell within the range of RT changes observed in our employed participants. A similar null effect was observed when participants were grouped based on hearing aid use.

**TABLE 3. Mean subjective ratings of fatigue and focus/attention obtained immediately before and after completing the sustained dual-task paradigm**

| | Fatigue | | | Focus/Attention | | |
|---|---|---|---|---|---|---|
| Condition | Pre | Post | Change | Pre | Post | Change |
| Unaided | 3.2 (0–8) | 7.3 (0–10) | 4.1 (0–8) | 2.5 (0–6) | 6.0 (0–9) | 3.5 (0–7) |
| Aided Basic | 3.4 (0–7) | 7.1 (2–10) | 3.7 (1–6) | 2.9 (0–7) | 6.3 (1–9) | 3.4 (1–6) |
| Aided Advanced | 3.4 (0–8) | 7.3 (0–10) | 3.9 (0–10) | 2.7 (0–6) | 6.0 (0–9) | 3.3 (0–8) |

*Values in parentheses show the range of scores and the change in score after testing.*

## DISCUSSION

### Effect of Hearing Aid Use on Listening Effort

In general, as listening conditions improve (e.g., better SNR) speech understanding improves, fewer explicit cognitive resources are needed to process speech, and thus listening effort may be reduced (McCoy et al. 2005; Zekveld et al. 2010; Rönnberg et al. 2011). Given the increase in audibility and improvements in speech recognition associated with hearing aid use, it would be reasonable to also expect a reduction in listening effort when comparing unaided and aided listening. Subjective data generally support this hypothesis (e.g., Humes et al. 1999; Hällgren et al. 2005; Noble & Gatehouse 2006).

However, in this study although there was a trend toward reduced ratings of effort and concentration when aided, the magnitude of reduction was small compared to prior work (Noble & Gatehouse 2006) and was not statistically significant (Table 2). The reasons for this difference between studies are unclear but could be related to differences in the time scales on which the subjective ratings were based. In this study, effort and concentration ratings were specific to experiences of “today” (the test day). However, no such limitations were imposed in other work using the SSQ. Rather responses were to reflect typical experiences over a longer time period. The reduced time frame used in this study may have reduced test sensitivity.

In addition, differences in subject characteristics between studies or differences in sample size could also play a role in the observed differences between studies. Noble and Gatehouse (2006) included participants with more hearing loss and greater asymmetry than participants in this study. Both these factors result in increased listening effort (Gatehouse & Noble 2004; McCoy et al. 2005) and thus allow for a greater reduction in effort when listening aided. Experience with the hearing aids used during the studies also differed. Participants in the study by Noble and Gatehouse (2006) had more experience wearing their own hearing aids (6 months) than present study participants had with the test aids (1–2 weeks). Thus acclimatization may have impacted listening effort and fatigue. However, the magnitude of effect, if any, is unknown. Finally, the present study sample size was relatively small, which reduced the power for detecting the small differences observed. The maximum power (1-β error probability) for any comparison of unaided and aided subjective ratings was ≤0.46.

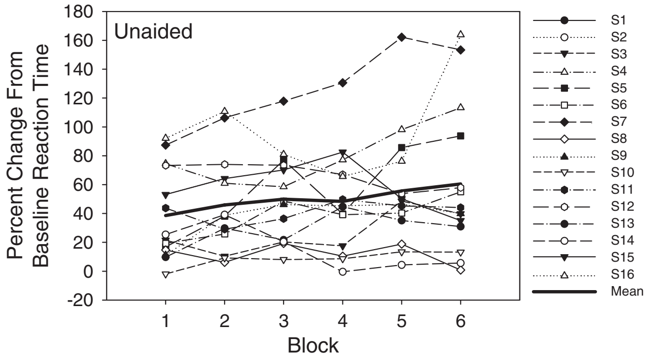

Fig. 6. Percent change from baseline reaction time as a function of block/time for individual participants in the unaided condition. Symbols connected with thin lines show individual data whereas the thick solid line shows the mean data for this condition.

Only a few studies have used objective measures to examine differences in unaided and aided listening effort in adults with hearing loss and even fewer have examined listening effort in noise using clinically fit hearing aids (Gatehouse & Gordon 1990; Hällgren et al. 2005; Picou et al. 2013). The present study adds to this literature. As expected, hearing aid use improved speech recognition and, in most cases, reduced listening effort as measured by improvements in secondary task performance. Specifically, aided word recall was significantly better than unaided, although the difference was small. Likewise, the relative increase in visual RTs (comparing single- and dual-task RTs) was less when aided. Averaged across six time blocks, the percent change in unaided dual-task RTs was almost 50%, compared with the 29 to 35% increases in the aided conditions (Fig. 5). These objective data support the hypothesis that cognitive processing demands/listening effort can be reduced via hearing aid use.

### Effect of Hearing Aid Use on Mental Fatigue

A primary goal of this study was to examine the effects of hearing aid use on mental fatigue resulting from sustained speech processing. A review of the literature revealed no studies using objective measures to quantify speech-processing–related fatigue. In fact, only a few studies (e.g., Bryant et al. 2004) have used speech materials in objective measures to quantify fatigue. In this study, fatigue was quantified objectively via changes in performance over the course of a cognitively demanding, speech-based, task. In both unaided and aided conditions word recognition and recall remained stable (or improved slightly) over time, suggesting these measures were resilient to fatigue effects. Likewise, dual-task visual RTs remained relatively stable over time when listening aided (basic or advanced). In contrast, when listening unaided, RTs systematically slowed, consistent with the development of mental fatigue. As the task progressed, and fatigue developed, participants may have systematically shifted cognitive resources from the visual RT task to the recognition and recall tasks to maintain optimal recognition and recall. Together, these findings suggest that the increase in audibility due to hearing aid gain, and the resulting improvement in the sensory representation of speech, reduced the listening effort/cognitive resources needed to process speech during the dual-task. This reduction in listening effort when aided appeared to minimize fatigue resulting from completion of the dual-task.

Because a small, but significant, improvement in word recognition over time was observed, an alternative hypothesis could be that fatigue, per se, did not develop. Rather, participants may have simply shifted the focus of their resources from the visual task to the word recognition task over time. However, this seems a less likely explanation, given that the small improvements in word recognition were similar to, or larger, in the aided (~1–2%) compared with unaided (~1%) conditions. In contrast, RTs were largest and increased significantly, only in the unaided condition. This pattern of results appears more consistent with a general learning effect than a shift in allocation of cognitive resources to overcome mental fatigue.

In contrast to the objective data, changes in subjective ratings of fatigue and attention were similar whether listening unaided or aided (Table 3). Likewise, correlations between subjective and objective measures of mental fatigue were weak or absent. This limited relationship is consistent with related work showing only a weak link between subjective and objective measures of listening effort (Larsby et al. 2005; Fraser et al. 2010; Zekveld et al. 2010; Gosselin & Gagné 2011). Similar discrepancies between subjective and objective measures of mental fatigue are also common. For example, Bryant et al. (2004) examined mental fatigue, objectively defined as a decrease in performance over time on a cognitively demanding task (the Paced Auditory Serial Addition Task), in individuals with and without multiple sclerosis (MS). Subjective ratings of fatigue were also obtained. Although subjective and objective measures showed greater mental fatigue for the individuals with MS, no relationship between the objective and subjective measures were observed. Similar findings have been reported in other populations with chronic fatigue syndrome, traumatic brain injury, and in healthy controls (Leavitt & DeLuca 2010). The results of the present study extend these findings to include a lack of association between subjective and objective estimates of mental fatigue resulting from sustained speech-processing demands in persons with hearing loss. This relatively common finding suggests that objective and subjective measures likely assess different aspects of listening effort and mental fatigue, and highlights the importance of including both types of measures in future work.

Although subjective and objective measures showed that sustained speech processing could lead to fatigue, Figure 6 and Table 3 highlight the fact that fatigue varied widely across participants. The factors responsible for this variability remain unclear. Correlation analyses suggested that the variability was not associated with any subject factor examined in this study. However, other factors such as motivation, cognitive ability, psychological state, lack of sleep, and task strategy may have played a role in modulating fatigue resulting from our dual-task (Davis 1946; Caldwell et al. 2005; Ackerman 2011). Additional work is needed to improve our understanding of factors that may increase or decrease susceptibility to speech-processing–related fatigue.

### Effects of Directional Processing and DNR Use During the Day on Listening Effort and Mental Fatigue

Also of interest was whether advanced signal processing features used during the day could reduce subjective ratings of listening effort and fatigue measured at the end of the day. If so, we hypothesized that a latent benefit might be reduced susceptibility to fatigue resulting from our cognitively demanding dual-task. Study results, however, showed subjective ratings of concentration, listening effort, and distractibility during the day and feelings of fatigue and focus at the end of the day were not significantly different whether these features were active or not (Tables 2 and 3). Likewise no differences between basic and advanced modes were observed on any subjective or objective measure of fatigue obtained during the experimental session.

This null effect may suggest a limited impact of directional and DNR technology on listening effort and fatigue experienced during the day. This could be because benefits from directional and DNR processing in real-world settings are often more subtle than those observed in the laboratory (Cord et al. 2004; Bentler 2005). If so, the subtle effect coupled with the relatively small sample size in the present study would reduce our ability to detect such differences. However, experimental design limitations in the present study make it difficult to draw firm conclusions and suggest further work in this area is needed.

For example, our method for subjectively rating effort may have lacked the sensitivity to detect subtle differences due to hearing aid use or advanced signal processing. It is likely that auditory demands, and benefits related to hearing aid use and signal processing, varied during the day. However, participants were forced to make subjective ratings using a single number to reflect concentration, effort, and distractibility throughout the entire day. This method may not be optimal for detecting benefits that vary over time and listening conditions. The fact that no differences in subjective ratings were observed between unaided and aided conditions highlights this potential lack of sensitivity.

Although select objective measures of fatigue (i.e., changes in visual RTs) did show a significant difference between unaided and aided conditions, there were no differences between the aided basic and advanced conditions. Again, however, experimental design limitations may have impacted these findings. Given the relatively low background noise level used, the directional processing and noise-reduction algorithms in the aids were inactive during dual-task testing. As such no differences in, at least baseline, word recognition abilities were expected. However, the similarity in single-task RTs, dual-task RTs, and word recall in the aided conditions suggest that latent cognitive benefits from activation of advanced features during the day, if present, were too small to be detected with this paradigm.

## CONCLUSIONS

1. Both subjective and select objective measures suggest that sustained speech-processing demands can lead to mental fatigue in persons with hearing loss.
2. The use of appropriate clinically fit hearing aids may reduce listening effort and susceptibility to mental fatigue due to sustained speech-processing demands, at least for some adults with mild to severe sensorineural hearing loss.

3. Variability in susceptibility to speech-processing–related fatigue was not strongly related to factors such as age, degree of hearing loss, motor processing speed (single-task visual RTs), or word recognition ability.
4. The subjective and objective measures of fatigue used in this study were not strongly correlated, suggesting they may be measuring different aspects of fatigue.
5. The use of directional processing and DNR algorithms during the day did not impact the subjective and objective measures of listening effort and fatigue used in this study. However, experimental design limitations suggest further work in this area is needed.

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