Purpose: The present study examined the effect of hearing aid use on cognitive test performance using a single-subject treatment design.

Method: Six participants 54 to 64 years old with sensorineural hearing loss were fitted with hearing aids. Participants used the hearing aids for approximately 8 hr each day for the duration of the study. A battery of cognitive tests was administered to participants during baseline (pre–hearing aid fitting), treatment (hearing aid use), and withdrawal (post–hearing aid use) study phases over a period of 6 months of hearing aid use.

Results: All participants showed significant improvements in performance on the cognitive test measures with hearing aid use. The most significant treatment effects were evidenced at 2 to 4 weeks of hearing aid use on the Listening Span Test and an auditory selective attention task. In many cases, cognitive performance scores returned to baseline levels after the participant stopped using the hearing aids.

Conclusion: The findings from this study are consistent with the hypothesis that hearing aid use may improve cognitive performance by improving audibility and decreasing the cognitive load of the listening task.

Currently, hearing aids are the most common and effective intervention for many individuals diagnosed with age-related hearing loss (Chisolm et al., 2007). However, although the majority of Americans with hearing loss could be successfully treated with hearing aids, only 23% use them, and an even lower 15% prevalence rate of hearing aid use is observed among adults with hearing loss in their 50s (Lin, 2012). This is concerning because left untreated, hearing loss has been shown to be associated with depression, withdrawal from social situations, reduced job performance, and diminished overall health (National Council on Aging, 1999). In addition, untreated hearing loss has also been shown to interfere with an individual’s cognitive abilities and intellectual function (Arlinger, Lunner, Lyxell, & Pichora-Fuller, 2009; Lin et al., 2013; Lindenberger & Baltes, 1994). In fact, peripheral auditory thresholds have been shown to be associated with working memory ability (Akeroyd, 2008), selective attention (Humes, Lee, & Coughlin, 2006), and perceptual processing speed (Lindenberger & Baltes, 1994; van Rooij & Plomp, 1990; Vaughan, Storzbach, & Furukawa, 2006). Untreated hearing loss has also been shown to be independently associated with accelerated cognitive decline, general cognitive impairment (Lin et al., 2013), and a higher incidence of dementia (Allen et al., 2003; Uhlman, Larson, Rees, Koepsell, & Duckert, 1989).

There are two main explanatory hypotheses for the association between cognitive and auditory variables (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994). The first is that a prolonged lack of auditory input from an untreated hearing loss could have a negative effect on the neural networks involved in certain cognitive abilities (Belin, Zatorre, Hoge, Evans, & Pike, 1999; Lindenberger & Baltes, 1994; Sekuler & Blake, 1987; Wong, Ettlinger, Sheppard, Gunasekera, & Dhar, 2010). That is, an auditory sensory impairment could result in a permanent cognitive degeneration (deprivation hypothesis; Baltes & Lindenberger, 1997). Second, it has also been suggested that untreated hearing loss could lead to a decline in cognitive performance because the cognitive resources normally used for higher-level comprehension, such as storing auditory information into memory, selectively attending to a listener, and processing auditory information quickly, must be used...
be their own controls and thereby making a control group level of the individual (Gast, 2010), allowing individuals to study to identify significant changes in performance at the aid use. An SSED was specifically chosen for the current tests before, during, and after 6 months of daily hearing which participants were administered a battery of cognitive study design (single-subject experimental design [SSED]) in ensures. We used a single-subject withdrawal experimental an individual adult
effectiveness of hearing aid use as a treatment to improve
sensory input to the brain, strengthening neural networks or visual sensory modalities (e.g., hearing aids may increase
whether the measures were administered in the auditory sensory modality, then improvements in performance on general cognitive tests of memory and executive function.
Thus, the effect of hearing aid use on cognition remains largely unclear (see Kalluri & Humes, 2012, for a review of the effect of hearing technology on cognition).
It is possible that the contradictory findings as to whether the remediation of hearing loss with hearing aids can improve cognitive performance may be due to differences in the sensory modality (i.e., auditory or visual) in which the cognitive test measures were administered in these studies. It stands to reason that if hearing aid use compensates only for impairments at the level of the auditory sensory input system, then improvements in performance measures are presented in the auditory modality (e.g., hearing aids may improve the audibility of the test items and/or test instructions, lessening the cognitive load of the listening task). However, if hearing aid use improves the efficiency of information-processing mechanisms at the level of the central nervous system, improved performance with hearing aids on cognitive measures would be evident whether the measures were administered in the auditory or visual sensory modalities (e.g., hearing aids may increase sensory input to the brain, strengthening neural networks involved in certain cognitive abilities).
The purpose of the present study was to identify the effectiveness of hearing aid use as a treatment to improve an individual adult’s performance on cognitive test measures. We used a single-subject withdrawal experimental study design (single-subject experimental design [SSED]) in which participants were administered a battery of cognitive tests before, during, and after 6 months of daily hearing aid use. An SSED was specifically chosen for the current study to identify significant changes in performance at the level of the individual (Gast, 2010), allowing individuals to be their own controls and thereby making a control group unnecessary. This was critical in the current study because we could not objectively verify when each participant first presented with clinically significant changes to the auditory system. Because declines in auditory perception are thought to be associated with degenerative changes in cognition (Lindenberger & Baltes, 1997), it was of particular importance to control for this variable at the level of the individual in the current study (see Byiers, Reichle, & Symons, 2012, for a comprehensive review of SSEDs).

Participants
Six adults 54 to 64 years of age participated in this study. Air-conduction thresholds at octave frequencies between 0.25 kHz and 8 kHz, and bone conduction thresholds at octave frequencies between 0.5 kHz and 2 kHz were measured in a double-walled, sound-attenuating booth using a GSI-61 audiometer with TDH-50 supra-aural earphones (American National Standards Institution, 2003). All participants had at least a mild sensorineural hearing loss, bilaterally, and no more than a 15-dB difference in hearing thresholds between ears at any audiometric frequency. See Figure 1 for hearing threshold levels averaged across the right and left ears for each participant.
None of the participants had worn or tried a hearing aid prior to participating in this study. Participants reported having difficulty understanding speech for an average of 4.5 years (SD = 4.4) in quiet listening conditions and 8.8 years (SD = 6.6) in noisy listening conditions. All participants were native speakers of English, had normal or corrected-normal near-field vision (e.g., 20/40 acuity) according to the Snellen eye chart, and passed the Short Portable Mental Health Status Questionnaire (Pfeiffer, 1975), a screening test of cognitive impairment. On average, participants had 18 years of education (SD = 2.5), and all were employed full time. Participants were paid an hourly wage for their participation. Institutional review board approval was obtained prior to

Figure 1. Unaided pure-tone thresholds (in dB hearing loss) averaged across the right and left ears for each of the six participants.
commencement of this study in accordance with the Syracuse University Institutional Review Board committee. See Table 1 for individual participant demographics.

**Hearing Aids**

Hearing aids were individually fitted to each participant upon completion of the baseline phase of this study. Starkey Xino receiver-in-the-canal hearing aids coupled to dome ear molds were fitted bilaterally. The hearing aids were programmed with Starkey Inspire software (Eden Prairie, MN) using the Desired Sensation Level (DSL v.5) prescriptive method (Scollie, 2006). The hearing aid fitting was verified with the Audioscan Verifit VF-1 real ear system (Dorchester, Ontario, Canada). Real ear-aided responses were within 5 dB across the prescribed target values for 0.25, 0.5, 1, and 2 kHz and within 10 dB at 4 kHz and 6 kHz for a speech input signal presented at 70 dB sound pressure level (SPL) for all six participants. The hearing aids were set to three programs: (a) omnidirectional, (b) adaptive directional/noise reduction, and (c) acoustic telephone.

Each participant received a hearing aid orientation session in which hearing aid use and care were explained. The Practical Hearing Aid Skills Test–Revised (PHAST-R; Desjardins & Doherty, 2009; Doherty & Desjardins, 2012), an eight-item questionnaire that measures basic hearing aid use and care skills, was administered to participants at their initial hearing aid–fitting session and at each treatment test session over 6 months of hearing aid use. This provided an objective measure of the participants’ ability to correctly use and care for their hearing aids. After each administration of the PHAST-R, participants were reinstructed on tasks they did not perform correctly or know how to perform. Data logging in the hearing aids was used to track each participant’s hours of hearing aid use. In addition, participants received a phone call every week when they were not seen in the lab to encourage hearing aid use and to troubleshoot any hearing aid problems. See Table 1 for participants’ PHAST-R scores and average daily hearing aid use over the 6 months.

The International Outcome Inventory for Hearing Aids (IOIHA; Cox et al., 2000), a subjective hearing aid outcomes measure, was administered to participants, via e-mail, at 20 weeks of hearing aid use. The IOIHA was used to assess the effectiveness of the hearing aid treatment in the current study (Cox et al., 2000). It consists of seven hearing aid outcome items including use, benefit, residual activity limitations, satisfaction, residual participant restrictions, impact on others, and quality of life. Participants were instructed to assign a value from 1 to 5 for each of the seven outcome items (i.e., higher scores indicate a more favorable outcome). Table 2 shows the IOIHA scores for each participant in this study. All participants scored within the norms for each test item (Cox, Alexander, & Beyer, 2003).

**Cognitive Test Battery**

Participants were administered a cognitive test battery that assessed working memory, selective attention, and processing speed abilities. We chose to measure these three aspects of cognitive function because they have been shown to be significantly associated with auditory acuity and to decrease with age (Akeroyd, 2008; Salthouse, 1985). Cognitive function was assessed using cognitive tests shown to be sensitive to the effects of aging (Akeroyd, 2008; Gatehouse & Gordon, 1990; Humes et al., 2006; Salthouse, 2000; Sliwinski & Buschke, 1999).

**Listening Span Test**

The Listening Span Test (Daneman & Carpenter, 1980), which is an auditory version of the Reading Span Test, was selected to measure working memory because the Reading Span Test has been shown to be one of the best predictors of speech recognition performance in noise in adults with hearing loss (Akeroyd, 2008; Desjardins & Doherty, 2013; Ng, Rudner, Lunner, Pedersen, & Rönnberg, 2013; Rönnberg et al., 2013). The methods used to administer the Listening Span Test in the current study were similar to those reported in previous studies (Ng et al., 2013; Ng, Rudner, Lunner, & Rönnberg, 2015; Pichora-Fuller, Schneider, & Daneman, 1995; Sarampalis, Kalluri, Edwards, & Hafer, 2009). The Listening Span Test in the present study consisted of sentences from the revised Speech Perception in Noise (R-SPIN) test.

Table 1. Participant demographics.

<table>
<thead>
<tr>
<th>Participant</th>
<th>Age (years)</th>
<th>HFPTA</th>
<th>Education (years)</th>
<th>Unaided Speech Recognition in Noise score (%)</th>
<th>PHAST-R (%)</th>
<th>Hearing aid use (hours)</th>
<th>Self-reported difficulty hearing (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>58</td>
<td>20</td>
<td>16</td>
<td>100</td>
<td>100</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>S2</td>
<td>62</td>
<td>37</td>
<td>18</td>
<td>92</td>
<td>97</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>S3</td>
<td>63</td>
<td>53</td>
<td>20</td>
<td>84</td>
<td>95</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>S4</td>
<td>54</td>
<td>43</td>
<td>16</td>
<td>88</td>
<td>97</td>
<td>7</td>
<td>20</td>
</tr>
<tr>
<td>S5</td>
<td>62</td>
<td>23</td>
<td>16</td>
<td>100</td>
<td>94</td>
<td>11</td>
<td>0</td>
</tr>
<tr>
<td>S6</td>
<td>64</td>
<td>40</td>
<td>22</td>
<td>92</td>
<td>89</td>
<td>5</td>
<td>10</td>
</tr>
</tbody>
</table>

Note. HFPTA = high-frequency pure-tone average of 1000, 2000, and 4000 Hz; PHAST-R = Practical Hearing Aid Skills Test–Revised.
(Bilger, Nuetzel, Rabinowitz, & Rzeczkowski, 1984), which is composed of eight lists of 50 sentences (400 total sentences). Each list of sentences contains 25 high-context sentences such that the final word in the sentence is predictable (e.g., “A chimpanzee is an ape”) and 25 low-context sentences in which the final word is not predictable (e.g., “She might have discussed the ape”). R-SPIN sentences were recorded by a female talker and digitized using the Computerized Speech Lab (Kay Elemetrics, Montvale, NJ) at a 44100 Hz sampling rate. They were presented at 70 dB SPL in a speech-shaped noise at +8 dB signal-to-noise ratio. The speech-shaped noise was generated in MATLAB using a 16-bit, 44.1-kHz sampling rate, by passing a Gaussian noise through a finite impulse response filter with a magnitude response equal to the long-term average speech spectrum of the 400 R-SPIN sentences. The R-SPIN sentences were presented to participants in a double-walled sound-attenuating booth in a pseudorandomized order (i.e., the same test list was never presented to a participant in consecutive test sessions) via a Sony multiscd compact disc changer (Sony Electronics Inc., Tokyo, Japan) routed through a GSI-61 audiometer to a GSI loudspeaker (Grason-Stadler, Eden Prairie, MN) located 1 m, at ear level, in front of the participant (0° azimuth). The background masker was played continuously throughout the task.

Participants were required to repeat the entire R-SPIN sentence they heard during a 4-s interval that followed the presentation of each sentence, then say “yes” if the sentence word was predictable from the sentence or “no” if the sentence word was not predictable from the sentence, and, last, to remember the final word in each sentence for later recall. The examiner recorded only the final key word in the sentence. The memory task was manipulated by varying the number of sentences in the set (i.e., two, four, and six). After all the sentences in a given set were presented, the experimenter prompted the participant to recall as many of the previously reported final key words as they could, verbally, and in any order. In each test session, 24 sentences were presented in three experimental conditions (set size two, four, six). Performance on the Listening Span Test was computed on the basis of the percentage of correctly recalled final key words.

**Auditory Selective Attention Task**

The Coordinate Response Measure corpus (CRM; Bolia, Nelson, Ericson, & Simpson, 2000) was used to measure auditory selective attention following the protocol described by Humes et al. (2006). The structure of each sentence in the CRM is identical, with each sentence using the form “Ready (call sign), go to (color) (number) now.” The CRM consists of every combination of eight call signs (Arrow, Baron, Charlie, Eagle, Hopper, Laker, Ringo, Tiger), four colors (blue, green, red, white), and eight numbers (1–8). Two similar sentences, one spoken by a male and the other by a female talker, were presented simultaneously to a single speaker at 70-dB SPL at 0° azimuth in a double-walled sound-attenuating booth via a Dell laptop using Inquisit 4 software (2013; Millisecond, Berkeley, CA). The target sentence was identified by a call sign, which was displayed orthographically in large font on a computer screen at the beginning of each trial. Participants were instructed to attend to the target sentence associated with a particular call-sign (“Baron”) and ignore a very similar competing message spoken by a different gender talker using a different call sign (e.g., “Charlie,” “Laker,” etc.). Participants were presented 32 presentations of competing sentence pairs in a practice block followed by 32 pairs in a test block. Participants were required to indicate the color and number coordinates of the target sentence by selecting one of four large rectangular buttons arranged in a column on the left side of the computer screen, labeled by both the color name and the color itself, and then selecting a number from a column of numbers listed 1 through 8 on the right side of the screen. Performance was calculated as the number of trials in which both the color and number were correct.

**Auditory Reaction Time Task**

An auditory reaction time task was used to measure auditory processing speed. The participant’s response time (measured in milliseconds) for the color response choice (i.e., blue, green, red, white; four-choice closed-set response) for each CRM trial was recorded via a Dell laptop using Inquisit 4 software. Between trials, participants kept their dominant hand on a fixed location on the computer desk. Performance was scored as the participant’s median reaction time for correct CRM color trials.

**Reading Span Test**

The English-language version of the Reading Span Test (Rönnberg, Arlinger, Lyxell, & Kinnefors, 1989) was used to assess participants’ working memory function. Participants were presented sentences one word at a time.
on a computer screen. Half of the sentences presented were nonsense (e.g., “The train sang a song”), and half were meaningful (e.g., “The girl brushed her teeth”). After reading each sentence, the participant was required to respond “yes” for a meaningful sentence and “no” for a nonsense sentence, during a 2-s interval after each sentence. The “yes” and “no” responses were not formally scored but were meant to ensure that the participant was attending to the entire sentence, not just the initial and final words. Three sets of three, four, five, and six sentences were presented to each participant. When all the sentences within a given set were presented, the software paused, and the word recall was displayed on a computer screen. The experimenter said either “first” or “last” in a randomized manner, and the participant was required to recall as many first or last words as possible in any order. Performance was determined by the percentage of correctly recalled words.

Visual Selective Attention Task

The Stroop test (Stroop, 1935) was used to assess participants’ selective attention in the visual mode. Participants were presented a list of words that are the names of colors printed in a color of ink different from the color name they represent (e.g., the word red printed in green ink). Participants had 45 s to name the color of ink of the printed words, as quickly as they could. Scores were calculated on the basis of the number of words named correctly.

Perceptual Processing Speed Test

The Digit Symbol Substitution test (DSST) from the Wechsler Adult Intelligence Scale—III (Wechsler, 1981) was used to assess participants’ perceptual speed of processing. In the DSST, participants were presented with a sheet of paper that has a code table displaying pairs of digits (1–9) and symbols. Beneath the code table were rows of double boxes with the digit in the top box and nothing in the bottom box. The participants were asked to use the code table to write which symbols were associated with each digit. The score is based on the number of correct symbols a person can identify in a 120-s period. The DSST was administered to participants in a paper-and-pencil format following the standardized test instructions for administration.

Study Design

A single-subject withdrawal study design (e.g., ABA design) was used to examine hearing aid use as a treatment for improving performance on cognitive test measures in individuals with hearing loss. In an SSED, each participant serves as his or her own control, thus allowing researchers to measure significant changes in performance at the individual level. This was particularly important in the current study because we could not accurately verify the number of years each individual has had a hearing loss. Because declines in auditory perception may be associated with declines in cognition (Lindenberger & Baltes, 1997), it was necessary to control for this variable at the level of the individual.

SSEDs are used routinely in speech-language pathology research to determine the effectiveness of specific treatment techniques for individual patients and are critical for the development and implementation of evidence-based practice in communication sciences and disorders (Apel, 2001). In addition, they have been used successfully in hearing aid research to identify successful treatment with hearing aids in children and adults (e.g., Gatehouse, 1992; Glista, Scollie, & Sulkers, 2012; Palmer, Adams, Bourgeois, Durrant, & Rossi, 1999). However, although this type of design offers a way of evaluating clinical significance, the extent to which the findings can be applied to the greater population of adults with hearing loss may be limited (see Byiers et al., 2012, for a review of SSED).

Data Collection

Data were collected over baseline (pre–hearing aid fitting), treatment (hearing aid use), and withdrawal study phases (post–hearing aid use; Byiers et al., 2012). In an SSED, baseline data (pre–hearing aid fitting) are used to establish a benchmark against which the individual’s test performance in the treatment phase and withdrawal phases can be compared.

Baseline Phase

The baseline phase was administered to participants before they were fit with the hearing aids. Three baseline test sessions were scheduled 1 week apart (Kazdin, 2011), during which the six cognitive tests were administered in a randomized order for each participant. To ensure the auditory cognitive test measures were audible during unaided testing, all auditory stimuli were presented to participants at 70 dB SPL, which was above the participants’ hearing thresholds. In addition, an unaided speech recognition in noise score was obtained for each participant during the first baseline test session for 25 R-SPIN sentences presented in a speech shaped noise at +8 dB signal-to-noise ratio following the standard test administration procedure for the R-SPIN. All six participants in the current study had good to excellent speech recognition in noise scores (see Table 1 for individual speech recognition in noise scores for the six participants).

Treatment Phase

This phase consisted of five test sessions in which the cognitive tests were administered to participants while they were wearing their hearing aids at 2, 4, 6, 12, and 24 weeks of hearing aid use in a randomized order. All testing in background noise was performed with the hearing aid set manually (by the examiner) to the noise reduction program. At the end of the last treatment test session (i.e., 24 weeks of hearing aid use), participants returned the hearing aids to the examiner.

Withdrawal Phase

Two weeks after returning the hearing aids, participants returned to the lab to complete the withdrawal test.
Results

Listening Span Test

Figure 2 shows the percentage of correct scores on the Listening Span Test (i.e., higher percentage scores indicate better performance) during the baseline, treatment, and withdrawal study phases for each of the six participants. Four of the six participants showed evidence of significant improvement in Listening Span Test scores with hearing aid use. Significant treatment effects were evidenced at 2 weeks of hearing aid use (i.e., Treatment Session 1) for the four participants. S1, who did not have a significant treatment effect with hearing aid use, was performing the task at ~95% correct performance prior to being fit with amplification. Thus, it is likely that we did not see a significant treatment effect for this participant because of a ceiling effect on unaided performance. S4 showed some improvement in treatment test scores compared with baseline test scores, but it did not meet the criteria to be considered a significant difference.

Table 3 shows effect sizes and the change in cognitive performance from the baseline study phase (i.e., prehearing aid fitting) to the treatment phase (i.e., aided testing) for each participant on each cognitive test. Hearing aids were a highly or moderately effective treatment for improving performance on the Listening Span Test in all four cases (effect sizes ranged from 1 to .8). Participants’ change in performance from the baseline phase (i.e., unaided) to the treatment phase (i.e., aided) of this study ranged from −1% to 17% across the six participants.

Two weeks after their last treatment test session, participants returned to the lab for the withdrawal test session, during which the cognitive test battery was administered unaided. We were interested in determining whether cognitive performance scores would return to baseline performance levels or if participants’ treatment performance scores would be maintained after completing the 6-month hearing aid trial. A significant withdrawal effect was evident for three of the four participants (S2, S5, and S6; see Figure 2). That is, the participants’ performance returned to near baseline performance levels after 2 weeks of not using the hearing aids. However, S3’s performance scores were significantly greater in the withdrawal phase compared with the baseline phase.

Auditory Selective Attention

Figure 3 shows the percentage of correct scores on the CRM (i.e., higher percentage scores indicate better performance) during the baseline, treatment, and withdrawal study phases for each of the six participants. All six participants showed evidence of significant improvement on the CRM with hearing aids. Significant treatment effects were evidenced at 2 weeks of hearing aid use (Treatment Session 1) for three participants (S1, S2, S3) and at 4 weeks of hearing aid use (Treatment Session 2) for three of the participants (S4, S5, and S6). Effect sizes indicated that hearing aids were a highly effective treatment for three
Figure 2. Percentage of correctly recalled words on the Listening Span Test as a function of hearing aid trial session. Each panel represents an individual study participant. Vertical dashed division lines separate the data by experimental phase: unaided baseline test scores (white squares), aided treatment test scores (black squares), unaided withdrawal test score (white square). Gray-shaded regions display the 95% critical difference (CD) of the three baseline scores (baseline CD).

Table 3. Relative change in performance level from baseline to treatment for each participant for each cognitive test measure.

<table>
<thead>
<tr>
<th>Participant</th>
<th>Listening Span Test (%)</th>
<th>CRM (%)</th>
<th>Auditory reaction time (ms)</th>
<th>Reading Span Test (%)</th>
<th>Stroop test (No. correct)</th>
<th>DSST (No. correct)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>–1</td>
<td>10* (1)</td>
<td>–229* (1)</td>
<td>10* (.4)</td>
<td>–5</td>
<td>3</td>
</tr>
<tr>
<td>S2</td>
<td>13* (.8)</td>
<td>15* (1)</td>
<td>–65</td>
<td>–8</td>
<td>5* (.4)</td>
<td>12* (.4)</td>
</tr>
<tr>
<td>S3</td>
<td>14* (1)</td>
<td>27* (1)</td>
<td>–114</td>
<td>18* (.6)</td>
<td>10* (.6)</td>
<td>4* (.4)</td>
</tr>
<tr>
<td>S4</td>
<td>7* (.8)</td>
<td>8* (.8)</td>
<td>74</td>
<td>8* (.8)</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>S5</td>
<td>9* (1)</td>
<td>12* (.8)</td>
<td>–164</td>
<td>13* (1)</td>
<td>2</td>
<td>10* (1)</td>
</tr>
<tr>
<td>S6</td>
<td>17* (.8)</td>
<td>19* (.8)</td>
<td>–161* (1)</td>
<td>10*</td>
<td>6* (.6)</td>
<td>6* (.8)</td>
</tr>
</tbody>
</table>

Note. Effect sizes of the treatment (proportion of data points exceeding the 95% baseline critical difference) are in parentheses for significant treatments. CRM = Corpus Response Measure; DSST = Digit Symbol Substitution Test.

*Significant treatment.
participants (S1, S2, and S3, effect size = 1) and a moderately effective treatment for S4, S5, and S6 (effect size = .8). Improvements in participants’ performance scores on the CRM from the baseline phase (i.e., unaided) to the treatment phase (i.e., aided) ranged from 8% to 27% (see Table 3). For four of the participants (S3, S4, S5, and S6), performance scores on the CRM returned to near baseline performance levels (i.e., significant withdrawal effect) during the withdrawal phase of the study. However, S1’s and S2’s performance on the test was significantly different in the withdrawal phase compared with the baseline phase.

**Auditory Reaction Time**

Figure 4 shows participants’ response times (milliseconds) on the auditory reaction time task (i.e., faster response times indicate better performance) during the baseline, treatment, and withdrawal study phases for each of the six participants. Two of the six participants (S1 and S6) showed significant evidence of improved auditory processing speed with amplification after 2 weeks of hearing aid use. Effect sizes indicated that hearing aids were a highly effective treatment in the two cases (effect size = 1). Participants’ reaction times from the baseline phase (e.g., unaided) to the treatment phase (e.g., aided) were 229 ms faster for S1 and 161 ms faster for S6 with hearing aid use (see Table 3). One of the participants (S1) had a significant withdrawal effect, indicating that performance returned to near baseline levels without hearing aids. However, S6’s performance was significantly different in the withdrawal phase compared with the baseline phase.

**Reading Span Test**

Figure 5 shows participants’ percentage correct scores on the Reading Span Test (i.e., higher percentage scores indicate better performance) during baseline, treatment, and withdrawal study phases for each of the six participants. Four of the six participants (S1, S3, S4, and S5) showed significant evidence of improved performance on the Reading Span Test with hearing aid use. Two of the participants’ (S4 and S5) scores were significantly improved at 2 to

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4 weeks of hearing aid use (Treatment Sessions 1 or 2), and two participants (S1 and S3) showed significant improvements in scores at 12 weeks of hearing aid use (Treatment Session 4). Effect sizes for the treatment were mixed; three participants (S1, S3, and S4) had effect sizes ranging from .4 to .6, indicating noneffective treatment with hearing aids, and one participant (S5) had a treatment effect size of 1, indicating that hearing aids were a highly effective treatment. Participants’ change in performance from the baseline phase (i.e., unaided) to the treatment phase (i.e., aided) of this study ranged from −8% to 18% (see Table 3). Significant withdrawal effects were seen for all four participants (S1, S3, S4, and S5). Thus, the participants’ performance on the Reading Span Test returned to baseline levels after not using hearing aids for 2 weeks.

**Visual Selective Attention**

Figure 6 shows participants’ performance on the Stroop test (i.e., higher number of correct responses indicates better performance) during the baseline, treatment, and withdrawal study phases for each of the six participants. Three of the six participants (S2, S3, and S6) showed significant evidence of improved performance on the Stroop test at 4 to 6 weeks of hearing aid use (Treatment Sessions 2 and 3). Effect sizes for the treatment indicated noneffective treatments for all three participants. Participants’ change in performance from the baseline phase (i.e., unaided) to the treatment phase (i.e., aided) of this study ranged from −5 to 10 (see Table 3). Significant withdrawal effects were evidenced for two (S2 and S3) of the three participants.

**Perceptual Processing Speed**

Figure 7 shows participants’ performance on the DSST (i.e., higher number of correct indicates better performance) during baseline, treatment, and withdrawal study phases for each of the six participants. Four of the six participants (S2, S3, S5, and S6) showed significant evidence of improved performance on the DSST with hearing aid use. Effect sizes for the treatment indicated moderately effective treatment for S5 and S6 and noneffective
treatments for S2 and S3. Participants’ change in performance from the baseline phase (i.e., unaided) to the treatment phase (i.e., aided) of this study ranged from 3 to 12 (see Table 3). A significant withdrawal effect was evidenced for S3 and S6. S2’s and S5’s performance was significantly different in the withdrawal phase compared with the baseline phase.

**Discussion**

In the current study, using an SSED, we examined the effect of hearing aid use on cognitive test performance in adults in their 50s and 60s with mild to moderate hearing loss. Hearing aid use was most effective in improving performance on cognitive test measures that were presented auditorily. Specifically, hearing aids were a highly or moderately effective treatment for improving performance on the Listening Span Test for four of the six participants and on the auditory selective attention task for six of six participants. Scores on these outcome measures improved from baseline to the first or second aided test session (i.e., 2 to 4 weeks of hearing aid use) in all cases. Performance on the Listening Span Test for all four participants, and on the CRM for four of the six participants, returned to baseline levels after they stopped using amplification (i.e., significant withdrawal effect).

These findings suggest that hearing aid use may compensate for impairments at the level of the auditory sensory input system, rather than at the level of the central nervous system. That is, the effects of hearing aid use may provide an immediate effect on encoding of working memory and selective attention ability, most likely by improving audibility and decreasing the cognitive load of the listening task. It stands to reason that hearing aids may lessen the cognitive processing resources a listener with hearing loss must expend to understand speech by effectively compensating for an individual’s auditory impairment and by improving the listening condition (e.g., better signal-to-noise ratio; Desjardins & Doherty, 2014; Mishra, Stenfelt, Lunner, Rönnberg, & Rudner, 2014; Murphy, McDowd, & Wilcox, 1999; Rabbitt, 1968; Rönnberg et al., 2013). If the benefit of hearing aid use on working memory function and/or selective attention were due to more of a long-term change to the nervous system (e.g., cognitive transfer effect),
performance should have improved with hearing aids on cognitive measures administered in both the auditory and visual sensory modalities, which was not the case.

In addition, if the treatment effect from hearing aid use were more of a long-term change to the central nervous system rather than an immediate perceptual effect from improved audibility, we would likely have seen a lasting change in cognitive performance scores after participants wore hearing aids for 6 months (i.e., nonsignificant withdrawal scores; Baltes & Lindenberger, 1997). However, participants’ cognitive performance scores during the treatment phase of this study (i.e., aided test scores) largely returned to baseline performance levels (i.e., pre-hearing aid fitting performance levels) when they stopped using the hearing aids. However, it is important to note that a significant limitation of the current study is that we collected data from only one withdrawal test session. It would have been best to collect data from three withdrawal sessions for each participant (Byiers et al., 2012). However, after completing their first withdrawal test session, all six of the participants expressed to the examiner that they did not want to be without hearing aids for any additional length of time. Thus, the study was ended after the first withdrawal test session. With only one withdrawal data point, it is difficult to determine withdrawal trends in the data. Thus, additional studies are needed to further examine the withdrawal effects on cognitive test scores following long-term hearing aid use.

Results from the present study are consistent with two recent studies that examined the effect of hearing aids on cognition (e.g., Dawes et al., 2015; Doherty & Desjardins, 2015). Dawes et al. (2015) investigated whether hearing aid use was associated with better cognitive performance using structural equation modeling. They found that hearing aid use was associated with better cognition through improved audibility rather than improved neuromechanisms. Similarly, Doherty and Desjardins (2015) examined the effect of hearing aids on auditory working memory performance in middle-aged and young older listeners compared with an age-matched control group not using hearing aids. They found that hearing aids provided immediate improvements in listeners’ working memory performance in background.
noise. However, there was no long-term improvement in working memory performance after 6 weeks of hearing aid use. They concluded that the effects of amplification on working memory function were more perceptual (immediate effect on encoding of working memory) than a cognitive transfer (long-term) effect.

In the current study, most participants did not have significant improvements in performance on the auditory processing speed task with hearing aids. Thus, hearing aid use improved performance scores on some of the cognitive tests but did not significantly lessen the response time required for a correct response in four of the six participants. This was surprising because several studies have shown that hearing aids may increase (e.g., make faster) the physical response to auditory stimuli (i.e., Downs, 1982; Gatehouse & Gordon, 1990). Gatehouse and Gordon (1990) measured listeners’ response times on an open-set sentence in noise task to determine the hearing aid benefit for listeners with mild to moderate hearing loss. Response times decreased significantly from the unaided to the aided listening conditions. They concluded that hearing aids made perceptual processing easier for individuals with hearing loss.

In the current study, it is possible that we did not observe significant improvements in auditory reaction time scores with hearing aid use because the closed-set four-choice auditory reaction time task used in the current study may have not been sensitive enough to detect changes in perceptual processing speed with amplification.

Although the most robust findings regarding the effects of hearing aid use on cognition were seen for the cognitive test measures presented auditorily, we did find significant treatment effects with hearing aids on the Reading Span Test in four (S1, S3, S4, and S5) participants and on the DSST in four (S2, S3, S5, and S6) participants. Unlike the Listening Span Test and the CRM, in which significant treatment effects were evident at 2 to 4 weeks of hearing aid use, significant treatment effects were not evidenced until 6 to 12 weeks of hearing aid use for two of the four participants on the Reading Span Test and two of the four participants on the DSST. This suggests that

Figure 7. Number of correct symbols on the Digit Symbol Substitution Test as a function of hearing aid trial. Each panel represents an individual study participant.
perhaps the effect of hearing aid use on cognitive measures presented visually has a different time course than cognitive tests presented auditorily. Two of the four participants on the DSST and all four participants on the Reading Span Test had significant withdrawal effects when they stopped using amplification (i.e., performance returned to baseline performance levels). Thus, it does not seem that there was a cognitive transfer or long-term improvement in performance on the Reading Span Test after 6 months of hearing aid use.

Of the six participants in this study, only one (S6) showed significant improvements in performance on five of the six cognitive tests with hearing aid use. Interestingly, this individual was the oldest participant (64 years old) in the current study and had relatively low (i.e., poorer) baseline levels of cognitive performance on the six cognitive measures compared with the other participants. Because of the relatively low baseline performance scores, it is possible that this individual had more room for the hearing aids to show improvements. Thus, the treatment effects of hearing aid use on cognition may differ depending on baseline levels of cognitive performance (i.e., pre-hearing aid fitting). This is an important finding to consider when designing larger group studies that look at the efficacy of hearing aid use on cognition.

It is also possible that the changes in performance on the cognitive tests observed in the current study may be due to the fact that people who begin to wear hearing aids could, after some time, engage in more auditory activity in everyday life. This increased activity could ultimately translate into preserving or enhancing cognitive health in these individuals. Thus, some of the effects we observed may not be due, simply, to the use of amplification but rather to the effects of amplification on cognitive stimulation in everyday life.

In summary, on the basis of the findings from the current study, it seems that using hearing aids, even when hearing loss is relatively mild and individuals are relatively young (i.e., 54–64 years old), may improve performance on some auditory cognitive tests. The majority of individuals in their 50s and 60s are still working full time, experiencing the earlier stages of age-related hearing loss, and have probably not sought treatment for their hearing impairment because “it isn’t that bad.” Although these individuals may be able to “get by” at work and in their day-to-day lives without a hearing aid, it is important to consider the potential impact of their hearing loss on their cognitive performance.

Conclusions

Hearing aids may be an effective treatment to mitigate performance on cognitive tests in adults. The positive treatment effects of hearing aid use are likely the result of improved audibility and a reduction in cognitive load. Although the results from this study demonstrated significant changes in performance with hearing aid use at an individual level, such findings may not be as robust at the group level. Thus, further research is warranted to examine the long-term and withdrawal effects of long-term hearing aid use on cognition.

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