Does Cognitive Function Affect Performance and Listening Effort During Bilateral Wireless Streaming in Hearing Aid Users?

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Introduction

A hearing aid is one of the most effective methods for alleviating the hearing difficulty of individuals with moderate-to-severe sensorineural and conductive hearing loss. Various technologies have been adopted to maximize the auditory benefit of hearing aids. The use of nonlinear amplification, which modifies the acoustic signal and provides the appropriate gain, is the most fundamental technique in hearing aids.

This method enhances performance in terms of audibility, comfort, and speech recognition [1]. In addition to nonlinear amplification of sound, noise reduction, directional microphones [2], and automatic acoustic-based program classifiers [3] are widely adopted and demonstrated as beneficial technologies to improve the audibility of hearing aids.

Wireless streaming technology (WT), which transmits sounds from a sound source directly to hearing aids, has been an important feature in hearing aids for decades [4]. From the well-known telecoil solution to more recent 2.4 GHz technologies, WT is an integrated part of hearing aid usage and has been widely adopted in recent hearing aids with increased battery lifespan. It thus fulfills the sound quality expectation of the
user in various listening conditions. For example, phone conversations can be difficult for hearing aid users due to feedback and a low signal-to-noise ratio. WT provides increased signal-to-noise ratio sound, and the wireless streamed sound without background noise can be clear and comfortable for hearing-impaired individuals [5].

However, it has been shown that the sound qualities of hearing aids using the same baseline streaming technologies can be significantly different between hearing aids. Moreover, previous studies have demonstrated that cognitive function may be relevant to hearing aid benefit, especially in the early adoption of hearing aids [6,7]. Considering that many hearing aid users are older, and that cognitive function may be compromised in this population, it is important to understand the role of cognitive function and its relationship to the benefit of various hearing aid technologies.

Hearing aid benefit can be assessed by various methods, including subjective and objective evaluations. Subjective benefit can be assessed using structured questionnaires, while objective measurement of hearing aid effectiveness can be achieved through real-ear insertion gain or real-ear aided response [8]. Several recent studies have demonstrated the benefit of hearing aids by assessing changes in listening effort and mental fatigue [9,10]. In addition to objective measurement, a self-report for listening effort measurement also has provided a suitable result for testing audiologic outcomes [11].

This study aimed to 1) investigate the benefit, assessed by the sentence/word recognition test and self-reporting listening effort, of bilateral wireless streaming in a noisy background for hearing aid users, and 2) analyze the associated factors for predicting the change in self-reported listening effort.

**Subjects and Methods**

**Participants**

Eighteen adults with symmetrical, bilateral, moderate-to-severe sensorineural hearing loss participated in the study. This study was approved by the Institutional Review Board (IRB) at Samsung Medical Center (IRB no. 2017-05-130). Informed consent was obtained from all participants prior to their involvement. To participate in the study, individuals were required to demonstrate a four-frequency average (500, 1,000, 2,000, and 4,000 Hz) hearing loss.

In addition to age and history of hearing aid use, cognitive function was assessed as a possible associated factor. Cognitive function was evaluated using the Montreal Cognitive Assessment (MoCA) [12], a one-page, 30-point screening tool for identifying mild cognitive impairment. This tool is administered in 10–15 minutes and assesses short-term memory, visuospatial abilities, executive function, phonemic fluency, verbal abstraction, attention, concentration, working memory, language, and orientation to time and place. Higher scores indicate better cognition. The effects of education were correct by adding one point to the total score for participants with 12 years of formal education or less. A highly experienced nurse provided instructions on the test to each participant and helped each individual correctly complete the test.

**Audiometric analysis**

Subjects were placed in a semi-anechoic chamber without their hearing aids and completed a hearing test using a GSI 61 audiometer (Grason-Stadler Inc., Eden Prairie, MN, USA) with TDH-39 earphones. Audiometric thresholds from 250 Hz to 8,000 Hz were obtained using the modified Hughson-Westlake method in both ears (Fig. 1).

**Study protocol**

Based on audiologic profiles, bilateral receiver-in-the-canal (RIC) hearing aids (LiNX 3D; ReSound, The GN Group, Ballestrup, Denmark) were fitted using a proprietary fitting formula by an experienced research audiologist (S. Park). Participants wore bilateral RIC hearing aids and performed the test to confirm sentence/word recognition ability in a mobile phone call situation with background noise. Since the study involved patients with moderate-to-severe hearing loss, the use of a RIC type hearing aid was deemed sufficient for hearing rehabilitation. To ensure a consistent analysis, all patients were fitted with the same type of hearing aid, specifically the RIC type.

**Test conditions**

Subjects were placed in a semi-anechoic chamber. Two mobile phones (Samsung Galaxy S7; Samsung, Suwon, South Ko-
rea) were used in the present study. One was for sound transmission, and the other was sound reception. The sound was played using a computer, which contained recorded sound files, and the sound was transmitted to the mobile phone through an audio transmission interface (Fireface UC; RME, Haimhausen, Germany). Using this mobile phone, the researchers called the other phone, which was designated as the transmitting phone. All participants heard the sound from the phone, with or without wireless connectivity. The mobile phone volume was adapted based on participant comfortable level.

All tests were performed in the following two conditions: WT-OFF or WT-ON conditions. In the WT-OFF condition, the participants listened to the phone through a hearing aid microphone. The mobile phone was set to the regular call mode, and sound was emitted through the speaker on the phone. The participant was instructed to use the phone in the manner they usually do for calls, positioning it close to the ear, thereby enabling them to hear through the phone’s speaker and microphone. In the WT-ON condition, sounds from the mobile phone were transmitted directly to the hearing aids using Bluetooth. In the WT-ON condition, the sound from the mobile phone was streamed bilaterally.

Noise

To assess the benefit of wireless streaming in a noisy background, multi-talker background noise was implemented during the phone conversation. Eight-talker babble noise using Korean speech sound was used in the present study. The level of noise was 75 dB SPL, and the noise was produced with four different speakers surrounding the participant at 45°, 135°, 225°, and 315°.

Scoring

Each participant listened to the sentences/words on the mobile phone under noisy conditions and was instructed to speak the sentences/words heard. The correct answer rates of the target sentence and the target word were evaluated. The possible score range for the correct answer regarding the target sentence was 0 to 10, and that for the target word was 0 to 40.

Listening effort test

After the tests, participants were asked to respond to a question about the amount of listening effort required to complete the listening task [11]. Participants used a 100-point scale to rate the amount of effort needed to complete each test. This test is designed to subjectively assess listening effort in noisy communication situations by having participants listen to sentence information and answer the speaker’s questions. The test consists of tasks where the participant listens to questions from the speaker through a hearing aid in a multi-speaker background noise during a conversation. The examiner evaluates the accuracy of the participant’s responses and, after the test is completed, assesses the participant’s subjective listening effort by having them self-rate their listening effort for each condition on a Visual Analog Scale, scored out of 100 points. The possible score range for listening effort rating was 0 to 100. The benefit of WT was defined as the difference in self-reporting scores (WT-OFF–WT-ON).

Statistical analysis

Wilcoxon signed rank sum test was performed to assess the benefit of WT. Age, history of hearing aid use, and cognitive function assessed by MoCA were considered as possible associated factors. The Mann–Whitney test was performed to assess the difference in outcome according to history of hearing aid use. Spearman’s correlation analysis was conducted to analyze the correlations between possible associated factors and benefit of WT. A two-sided p-value <0.05 was considered statistically significant. All data were analyzed with SPSS software, version 20.0 (IBM Corp., Armonk, NY, USA).

Results

The median age of participants was 62.5 years and ranged from 27 to 70 years. Eleven patients were previous hearing aid users and 7 patients had no prior experience with hearing aids (one unknown). The median duration of hearing aid use was 60 months, ranging from 4 to 96 months. The mean MoCA score of the study population was 27.0 (23–30). The correlation between age and MoCA was not significant (p=0.30, Spearman’s correlation analysis); however, except for one outlier, a negative association between age and MoCA was demonstrated (Fig. 2). Baseline characteristics of the participants are given in Table 1.

The correct answer rate of the target sentence according to test condition is shown in Fig. 3. Mean sentence answer score in WT-OFF was 6.6±2.5 and in WT-ON was 9.3±0.5, a significant difference (p=0.001). The correct answer rate for the target word according to test condition is shown in Fig. 4. The mean word answer score in WT-OFF was 30.0±10.1 and in WT-ON was 39.1±0.7, a significant difference (p=0.001). Listening effort in background noise was significantly reduced with WT in hearing aids. The mean WT-OFF score was 85.5 (60–100), and the WT-ON score was 72.5 (20–95), a significant difference (p=0.02 (Fig. 5). Age did not show a significant correlation with benefit of WT (p=0.38). No significant differences in hearing performance were observed according to MoCA.
scores in the three states of unaided, WT-OFF, and WT-ON. History of hearing aid use did not show a difference in benefit of WT ($p=0.84$, Mann–Whitney test). MoCA score showed a significant positive correlation with benefit of WT ($\rho=0.59$, $p=0.01$) (Fig. 6).

**Discussion**

This study was designed to investigate whether WT affects sentence/word recognition ability and listening effort and if cognitive function subtests can predict performance between WT-OFF and WT-ON. First, the researchers described the results of change in sentence/word recognition ability and self-rated listening effort depending on use of WT. During the WT-ON condition, participants reported better sentence/word recognition ability and less listening effort to conduct the task. The result indicates that WT has a significant effect
on audibility and alleviates self-rated listening effort in noisy background conditions.

One large-scale survey reported that 31% of hearing aid users were not satisfied with the sound during phone conversations on a mobile phone. Moreover, hearing aid users were not satisfied with the hearing aid in noisy situations (39%) or in windy conditions (42%).

Classic hearing aids can offer satisfactory sound perception in relatively quiet environments. In noisy environments, however, they provide less than adequate performance because they also amplify environmental noise, and it is difficult to pick up clear target sounds in common real-world environments. In addition, people with hearing loss usually require a much higher signal-to-noise ratio than normal-hearing people for adequate speech recognition.

Using wireless connectivity, hearing aids can minimize the interference of noise during amplification of the target sound. This can be beneficial for increasing the signal-to-noise ratio in noisy situations and challenging listening environments, such as phone conversations. In addition, wireless streaming offers binaural sound presentation, which can provide true binaural hearing, including loudness summation. This can be beneficial in improving the satisfaction of hearing aid users. Of note is that the benefit of WT (the change of self-rated listening effort) differed among study participants. This suggests that unknown participant factors may have a role in the degree of benefit for hearing aid functions.

Several hearing aid technologies, such as noise reduction, directional microphones, automatic acoustic-based program classifiers, and wireless streaming are widely adopted and have been assessed with regard to the audibility of hearing aids. However, many studies have reported large interindividual variation in the benefit of each technology [13,14]. Although it is expected that a hearing aid’s various functions will be beneficial, the results are not consistent; one possible explanation is that a hearing aid wearer is usually an elderly person. It is well-documented that, as people age, they experience some decrease in cognitive abilities, and this cognitive deterioration is associated with age-related neural changes [15,16]. In addition, the degree of cognitive deterioration has large interindividual variation [17]. Various genetic and lifestyle factors support brain maintenance in aging, and interventions can be designed to promote maintenance of brain structure and function in later life [18]. Therefore, these interindividual variations may be associated with adaptation in newly-developed hearing aid technologies. The researchers hypothesized that cognitive function might affect adaptation to various hearing aid technologies and be a predictor of benefit.

In elderly patients with impaired cognitive function, there may be difficulties in operating a mobile phone, limiting the full utilization of the advantages of wireless connectivity. Nevertheless, Figs. 3 and 4 indicate that there are substantial benefits from using WT, regardless of the degree of cognitive function. These findings suggest that if the features of hearing aids are utilized effectively, most patients with hearing impairment can potentially benefit from the useful features of hearing aids.

The present study demonstrated that cognitive function, assessed by MoCA, showed a positive correlation with benefit of wireless connectivity in hearing aid users. However, regarding the MoCA score, no significant difference was observed in hearing aid performance between WT-OFF and WT-ON conditions. Higher MoCA scores indicated higher cognitive function, and higher WT-OFF and WT-ON scores indicate greater benefit of WT. This positive correlation suggests that cognitive function may be a useful predictor of the benefit of wireless streaming in hearing aid users. Study results support previous findings that cognitive function predicts listening effort performance during complex tasks in normally aging adults. Harvey, et al. [19] stated that cognitive function measured by the subtest of the Woodcock-Johnson III (Memory for Words, Auditory Working Memory, Visual

Fig. 6. Correlation analysis with benefits of WT. A: Age did not show a significant correlation with benefit of WT. B: History of hearing aid use did not show a difference in benefit of WT. C: Positive correlation between MoCA and benefit of wireless streaming activation (WT) as assessed by self-rated listening effort (p=0.59, ρ=0.01, Spearman’s correlation analysis). WT, wireless streaming technology; HA, hearing aid; MoCA, Montreal Cognitive Assessment.
Matching and Decision Speed) assessment predicts listening-effort performance during tasks. In this study, discrepancies in accuracy and reaction time performance were quantified as indicators of listening effort. Meanwhile, Zekveld, et al. [20] demonstrated that better performances on the text reception threshold, used as a cognitive test, were associated with higher listening effort in the hearing impairment group. In this research, higher listening effort was measured through larger peak dilation amplitudes and extended pupil response durations during pupillometry.

This study had some limitations. First, the number of study participants was small and therefore limited the analysis of other confounding factors that may have affected study results. Second, some participants did not have enough time to adapt to unfamiliar hearing aid types, and real-ear measurements to confirm the best fitting status were not performed. Adaptation to hearing aids is an important process for maximizing their benefits, and real-ear measurement is helpful in achieving more accurate fittings [21]; these should be considered when results are interpreted. Third, results were limited to WT with bilateral RIC hearing aids. Fourth, the WT-OFF condition does not represent the bilateral hearing in real world. To simulate the environment in which hearing aid users use mobile phones in their daily lives, we positioned a mobile phone close to one ear, allowing the participant to hear the sound. Although the sound transmission differs from bilateral hearing, where sound is transmitted via wireless streaming, it is crucial to note that the research aims to assess the benefits of wireless streaming in comparison to daily usage scenarios. Therefore, the advantages of bilateral hearing are expected to be clearly reflected in the overall effects observed.

However, the study had sufficient strength to suggest a number of results. It was the first study to analyze the association between cognitive function and wireless streaming in hearing aids. In addition, the results demonstrated the benefit of wireless streaming using sentence/word recognition tests and listening effort even though participants were not fully adapted to the new hearing aids. Therefore, future studies are needed to demonstrate the benefit of wireless connectivity in long-term hearing aid users.

In conclusion, the study demonstrated that bilateral wireless streaming could enhance sentence/word recognition and decrease listening effort during phone use for hearing aid users, and the benefit was related to cognitive function. Thus, cognitive function may be a useful predictor of benefit of wireless streaming in hearing aid users, and this finding could be incorporated into patient counseling and prescription of hearing aids.

Cognitive Function and Listening Effort in Hearing Aid Users

Conflicts of Interest
The authors have no financial conflicts of interest.

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REFERENCES
9) Hornsby BW. The effects of hearing aid use on listening effort and mental fatigue associated with sustained speech processing demands. Ear Hear 2013;34:523-34.
12) Nasreddine ZS, Phillips NA, Bédirian V, Charbonneau S, Whitehead...


