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Research Article

The Effects of Directional Processing on Objective and Subjective Listening Effort

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Purpose: The purposes of this investigation were (a) to evaluate the effects of hearing aid directional processing on subjective and objective listening effort and (b) to investigate the potential relationships between subjective and objective measures of effort.

Method: Sixteen adults with mild to severe hearing loss were tested with study hearing aids programmed with 3 settings: omnidirectional, fixed directional, and bilateral beamformer. A dual-task paradigm and subjective ratings were used to assess objective and subjective listening effort, respectively, in 2 signal-to-noise ratios. Testing occurred in rooms with either low or moderate reverberation.

Results: Directional processing improved subjective and objective listening effort, although benefit for objective effort was found only in moderate reverberation. Subjective reports of work and tiredness were more highly correlated with word recognition performance than objective listening effort. However, subjective ratings about control were significantly correlated with objective listening effort.

Conclusions: Directional microphone technology in hearing aids has the potential to improve listening effort in moderately reverberant environments. In addition, subjective questions that probe a listener's desire to exercise control may be a viable method for eliciting ratings that are significantly related to objective listening effort.

Understanding speech in noise is difficult for listeners with sensorineural hearing loss (Dirks, Morgan, & Dubno, 1982; Plomp, 1978). They often require a better signal-to-noise ratio (SNR) than their peers with typical hearing to achieve similar speech recognition performance (Festen & Plomp, 1986; Hawkins & Yacullo, 1984; Peters, Moore, & Baer, 1998; Plomp, 1986). As a result, remediation for sensorineural hearing loss often involves attempts to improve the SNR. In hearing aids, improving the SNR can be accomplished with first-order directional processing, which implements two omnidirectional microphones, or two microphone openings, in a single microphone capsule. As long as the desired signal arrives from the direction with high sensitivity (often the front) and the noise arrives from the direction with low sensitivity (often behind), directional processing can improve the SNR (Ricketts & Dittberner, 2002). Directional processing has been implemented for decades in hearing aids and has been shown to improve speech recognition in noise across a wide range of laboratory and simulated real-world environments (e.g., Hawkins & Yacullo, 1984; Madison & Hawkins, 1983; Preves, Sammeth, & Wynne, 1999; Ricketts, 2000; Ricketts & Hornsby, 2006; Wu, 2010). Despite the benefits of directional processing, speech recognition in noise is a common clinical complaint for hearing aid users (Kochkin, 2007; McCormack & Fortnum, 2013; Takahashi et al., 2007).

Advanced microphone array technologies have been introduced in an attempt to further improve SNR and to alleviate continued difficulty understanding in noise. One such technology implements more than two microphones into a higher order array, further enhancing hearing aid directivity (Ricketts & Dittberner, 2002). For bilateral hearing aid fittings, combining the information from all four microphones in both hearing aids is one way to achieve such an array. For the purposes of this article, the specific processing that generates a microphone array using all four bilateral hearing microphones is called a *bilateral beamformer.* Bilateral beamformers can significantly improve the SNR for signals of interest arriving from the front (Cornelis, Moonen, & Wouters, 2011; Sriram, Ashish, & Kees, 2008) and thus can be used in noisy situations with a single talker located in the direction of maximum sensitivity (Lotter & Vary, 2006; Peterson, Durlach, Rabinowitz, & Zurek, 1987). However, the improvements in SNR may be offset by other consequences, particularly as a result of the distortion of natural binaural information. In a simple

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bilateral beamformer, the hearing aids combine information from the microphones at both ears, presenting a single highly directional signal to both hearing aids and thus altering the interaural cues. The distortion of these interaural cues could have negative consequences for hearing aid users. As a result, all commercial implementations attempt to restore some of the interaural information—for example, by band limiting the frequency region over which the bilateral beamformer is active or by introducing interaural differences that are based on average head-related transforms. Previous results suggest that, like traditional directional processing, commercial bilateral beamformers can improve speech in noise performance when the speech originates from the front and the noise originates from other azimuths (Best, Mejia, Freeston, Van Hoesel, & Dillon, 2015; Picou, Aspell, & Ricketts, 2014).

Although both traditional first-order directional processing and bilateral beamformers can improve speech in noise for hearing aid users, it is also of scientific and clinical interest to investigate the cognitive cost for listeners attempting to understand speech while using directional processing. In other words, do these directional technologies affect listening effort? Listening effort is often described as the cognitive resources necessary for speech recognition (Fraser, Gagne, Alepins, & Dubois, 2010; Hicks & Tharpe, 2002) and can be modeled using the Ease of Language Understanding (ELU) model (Rönnberg et al., 2013; Rönnberg, Rudner, Foo, & Lunner, 2008). This model suggests that language inputs are rapidly and automatically bound together and compared to long-term memory stores. If there is a match between the input and memory stores, a listener can easily understand the speech. Instead, if there is a mismatch between the input and memory stores, cognitive resources must be explicitly deployed, and speech understanding is effortful.

On the basis of the ELU model, it would be predicted that any technology that improves the clarity of the language input would facilitate the comparison to long-term memory, consequently decreasing listening effort. Technologies that are good candidates for potentially improving listening effort are those that improve the signal clarity without adding additional distortions. On the other hand, a technology might increase listening effort if it distorted the signal or was unnatural. It is conceivable that a hearing aid technology could affect speech recognition and listening effort domains separately. For example, a technology could dramatically improve the SNR, allowing better speech recognition. On the other hand, this same processing could distort some aspect of the signal, thus impeding the comparison between language input and long-term memory store and thereby increasing listening effort.

Hearing Aid Technology and Listening Effort

There have been several investigations into the effects of advanced signal processing on listening effort, primarily focused on digital noise reduction and directional processing. Regarding digital noise reduction, results of previous investigations generally support the benefits of the technology on listening effort, especially in difficult SNRs, even when speech recognition was not affected (Desjardins & Doherty, 2014; Sarampalis, Kalluri, Edwards, & Hafter, 2009). On the other hand, previous results examining the effects of directional processing on listening effort have failed to demonstrate benefits for listeners with hearing loss. For example, Hornsby (2013) evaluated the effects of hearing aid use and advanced hearing aid processing (noise reduction, directional microphones) on sustained listening effort using a dual-task memory paradigm. The results suggested that hearing aids reduced listening effort and fatigue, whereas the advanced processing offered no additional benefits for either effort or fatigue. However, the author explained that the lack of significant additional benefits might be related to study methodology. The background noise level used (55 dBA overall) may not have been high enough to activate the directional processing or noise reduction algorithms. Therefore, the effects of directional processing on listening effort may not have been evaluated in this particular study.

Wu et al. (2014) also found nonsignificant effects of directional processing on listening effort for listeners with hearing loss. The authors used two dual-task paradigms in which sentence-in-noise recognition was the primary task and the secondary task was either a driving task or a decision task with a visual stimulus. The sentence recognition stimuli were presented at −1 dB SNR with background noise levels of approximately 75 dB. Regardless of the dual-task paradigm used, there was no benefit of directional processing on listening effort, despite improvements in sentence recognition performance. On the other hand, directional benefits were measured for listeners with typical hearing who were tested using the decision-based dual task. The authors hypothesized that, for listeners with hearing loss only, the task was too difficult to be sensitive to the effects of directional processing.

Last, in an investigation of the potential benefits and limitations of traditional directional processing and bilateral beamforming, Picou et al. (2014) used a simple dual-task paradigm to evaluate the effects of these two types of directional processing on listening effort. The background noise level was moderate (65 dB). Although there was a trend for both types of directional processing to reduce listening effort, the effects were small (approximately 10-ms improvement in response times) and not statistically significant. However, subsequent investigations from the same authors suggested that the simple dual task used in that study might not be sensitive to factors that affect listening effort. Picou and Ricketts (2014a) investigated three dual-task paradigms in which the secondary tasks varied in either complexity or depth of linguistic processing. These results revealed that the secondary task that required deeper linguistic processing was more sensitive to the effects of background noise for listeners with typical and impaired hearing. Therefore, it is possible that the nonsignificant findings of Picou et al. (2014) might have been significant if a more sensitive paradigm was used.

Another important finding from the Picou et al. (2014) investigation was that the bilateral beamformer benefits for sentence recognition varied as a function of degree of reverberation. The bilateral beamformer provided additional benefits for sentence recognition in noise relative to the traditional directional processing only in moderate reverberation (T30 = 675 ms) and not in low reverberation (T30 < 100 ms), where T30 is defined as double the time it takes for the energy in a room to decay from 5 to 35 dB below the initial level (International Standards Organization, 2009). Although the authors did not investigate the interaction between reverberation and directional processing for listening effort, these results suggest that degree of reverberation might modulate the benefits of directional processing for listening effort.

Subjective Versus Objective Effort

In addition to reverberation, another factor that might interact with directional processing and listening effort is measurement technique. Researchers use a variety of measurement techniques to assess listening effort. Objective techniques often are based on physiological state changes—for example, skin conductance (Mackersie & Cones, 2011) or pupil dilation (Zekveld, Kramer, & Festen, 2010)—or are based on the idea that humans have limited cognitive resources (Kahneman, 1973). Measurements that are based on the latter principle draw inferences about listening effort by measuring declines in recall (e.g., McCoy et al., 2005; Picou, Ricketts, & Hornsby, 2011; Rabbitt, 1968), increases in response times (e.g., Gatehouse & Gordon, 1990; Picou & Ricketts, 2014a), or performance impairments on a secondary task (e.g., Desjardins & Doherty, 2014). In addition to these objective indices of listening effort, many investigators use subjective measures in which participants are asked to rate their effort after a particular task (e.g., Brons, Houben, & Dreschler, 2014; Picou & Ricketts, 2014b; Rennies, Schepker, Holube, & Kollmeier, 2014).

Although all of the aforementioned measurements are presumed to reflect listening effort, many investigators have suggested that subjective and objective measures reflect different underlying mechanisms (e.g., Downs & Crum, 1978; Feuerstein, 1992; Hicks & Tharpe, 2002; Johnson, Xu, Cox, & Pendergraft, 2015; Pals, Sarampalis, & Başkent, 2013). For example, Feuerstein (1992) compared monaural and binaural listening using a dual-task paradigm in which the secondary task was a physical response to a visual probe. Feuerstein also collected subjective ratings of ease of listening. Results indicated that the pattern of results was different for the two outcomes—that is, the objective and subjective measures were differentially sensitive to the effects of binaural listening. In addition, Feuerstein calculated correlations between speech recognition performance, response times, and subjective ratings. Subjective ratings were correlated with speech recognition scores and not response times. One interpretation of this pattern of results could be that participants were rating their performance rather than their objective effort. Other authors have also reported that subjective ratings follow speech recognition performance rather than objectively measured listening effort (e.g., Downs & Crum, 1978; Fraser et al., 2010; Gosselin & Gagné, 2011), although this pattern has not been consistently reported in all studies (e.g., Hallgren, Larsby, Lyxell, & Arlinger, 2005; Johnson et al., 2015).

One possible explanation for the disparity between subjective and objective measures is that listeners may not be overtly aware of changes in mental effort. When asked to rate their effort, they may instead focus on rating their performance because performance may be more easily quantifiable through introspection than effort. The idea that respondents might answer questions on the basis of their performance rather than their mental effort is consistent with the work of Kahneman (cf. Kahneman, 2003; Kahneman & Frederick, 2002), who described an attribute substitution heuristic. When asked to assess a multidimensional phenomenon, people evaluate a simpler heuristic attribute rather than the target attribute. In this case, because mental effort (the target attribute) may be difficult to perceptually quantify, participants may instead prefer to rate their performance (the heuristic attribute). Therefore, participant ratings of effort or ease of listening may not correlate with objective listening effort because participants would be substituting a heuristic attribute (performance) for the target attribute (effort).

One possible solution would be to classify subjective ratings as invalid indicators of effort if people cannot readily rate the phenomenon. However, this solution is undesirable for a number of reasons, most notably that patients often complain about their effort clinically. An alternative solution could be to modify the instructions of the subjective rating question to find terminology that helps participants reflect on their effort rather than their performance. There are myriad options for terminology that could be used to potentially elicit subjective ratings that correlate with objective effort. For example, participants could be instructed to rate their effort, with explicit instruction to separate effort and performance. According to Kahneman (2003), attribute substitution is a product of automatic processing. If a participant's attention is drawn to the difference between target and heuristic attributes, the participant might rate effort instead of performance.

Another alternative would be to use a different word that is more easily relatable. For example, the concepts of effort or work might be difficult to quantify, but many people readily and routinely rate their tiredness. The terms *tired* and *effort* would be expected to reflect different phenomena; *tired* might be more closely related to fatigue than effort. Although sustained increases in listening effort have been linked to listening fatigue (Hornsby, 2013), the relationship is not always straightforward and certainly is multifaceted. Despite these limitations, if use of the word *tired* in a subjective rating yielded responses that were correlated with objective effort, it is possible that future investigations could use the word *tired* despite its theoretical limitations.

Last, in lieu of asking participants to rate their effort, participants could be asked to rate the degree to which they would do something to control the situation. Participants may not be explicitly aware of their effort but may be keenly aware that they are struggling and want to take action to improve the situation. When tasks become difficult, listeners generally choose either to avoid the situation altogether or to do something to control the situation (Hallberg & Barrenäs, 1995; Hallberg & Carlsson, 1991). Controlling a situation includes behaviors such as asking for repetition, trying to see the talker's face, or moving to a quieter room (Demorest & Erdman, 1986; Hallberg & Carlsson, 1991). In a laboratory setting, avoiding the situation is impractical because listeners are already participating, and data are often excluded when participants withdraw from studies. However, these participants may be acutely aware of a desire to do something to change the situation. This desire may reflect their listening effort. Thus, asking participants to rate the extent to which they want to do something to control or improve the situation may elicit subjective ratings that correlate with objective listening effort.

Purpose

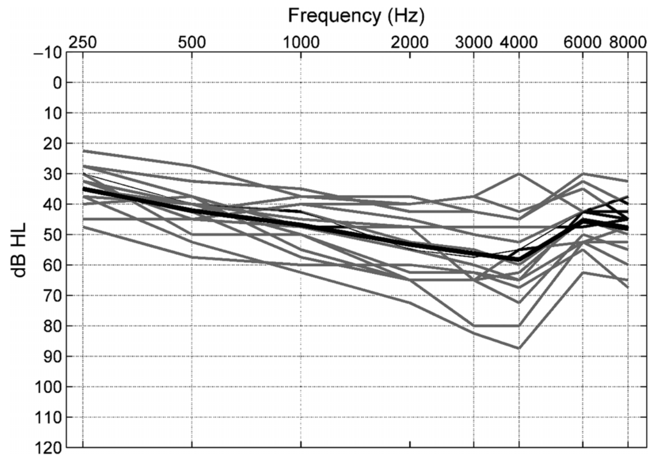
The purpose of this investigation was to test the hypothesis that hearing aid directional processing will improve listening effort for listeners with hearing loss. A sensitive dual-task paradigm was used to evaluate word recognition and response times with three microphone settings (omnidirectional, traditional directional, bilateral beamformer) at two SNRs (moderate, difficult) in two levels of reverberation (low, moderate). A second purpose of this study was to investigate the relationship between objective and subjective indices of listening effort. Specific terminology used included asking about (a) the work required to understand (acknowledging that this is separate from performance), (b) tiredness, and (c) the degree to which a participant would do something to control the situation.

Method

Participants

Sixteen adults aged 23 to 79 years (M = 62.6, SD = 14.4) with sensorineural hearing loss (as defined by air–bone gaps of < 15 dB HL and normal acoustic immittance findings) participated in this study. Figure 1 displays the individual and mean air-conduction thresholds for study participants averaged across left and right ears. Seven participants were experienced hearing aid users (M = 8.2 years, SD = 7.0), although no participant owned hearing aids with bilateral beamforming. Participants were fluent in English and had no reported history of neurological or cognitive disorders. All testing was conducted with the approval of Vanderbilt University Medical Center's institutional review board. Participants were compensated for their time monetarily at an hourly rate. They did not keep the study hearing aids and were not given the option to purchase them.

Figure 1. Mean pure-tone audiometric thresholds between left and right ears for individual study participants (gray lines) and on average (black line). Values are in dB HL based on ANSI S.36-1996.



Hearing Aid Fitting

Prior to testing, participants were fitted with behind-the-ear hearing aids (Phonak Ambra, Stäfa, Switzerland) with occluding, noncustom eartips. None of the test participants were users of this hearing aid model at the time of testing. The hearing aids were programmed with three manually accessible programs: omnidirectional, traditional fixed directional, and proprietary cue-preserving bilateral beamformer. The manufacturer-reported average directivity indices (500, 1000, 2000, and 4000 Hz) for omnidirectional, fixed directional, and bilateral beamformer were approximately −1.1, 4.9, and 6.9 dB, respectively. The interaural cue preservation of these hearing aids previously was evaluated and reported on by Picou et al. (2014). All other hearing aid sound processing features (frequency lowering, training, automatic switching, digital noise reduction, wind reduction, and impulse noise reduction) were disabled except the feedback reduction algorithm. Acoustic feedback pathways were modeled individually with the manufacturer's programming software, and the feedback reduction was set to *strong* to avoid acoustic feedback during testing.

During the fitting, the hearing aid gain was manipulated with programming software to be within ±5 dB of National Acoustic Laboratories nonlinear fitting procedure (Version 2) real-ear aided response prescriptive targets (Keidser, Dillon, Carter, & O'Brien, 2012). Match to target was verified using probe microphone measurements with an AudioScan Verifit (Version 3.2; Dorchester, Ontario, Canada) and a recorded speech passage ("the carrot passage") presented at 65 dBA with the loudspeaker at 0° azimuth. The three programs were verified to be identical for signals originating from 0° azimuth.

Stimuli

Dual-Task Paradigm

This study used the semantic dual-task paradigm described by Picou and Ricketts (2014a) in which the primary task was monosyllable word recognition and the secondary task was word categorization. Participants indicated as quickly as possible whether the word heard could be a noun. This dual-task paradigm requires increased depth of processing (Craik & Lockhart, 1972; Eysenck & Eysenck, 1979) relative to more traditional dual-task paradigms in which the secondary task is often unrelated to the primary task (e.g., pressing a button when a light flashes). If participants judged the word to be a noun, they made a button press on a USB keypad; otherwise, no button press was expected. Participants were instructed to make their decision and button response as quickly as possible and before repeating the word. Mean response time was taken as a measure of objective listening effort. All responses were included in calculating mean response times because (a) correct identification was not of interest, (b) noun recognition skill was not of interest, and (c) correct identification of nouns depended on whether the word was heard correctly. For a detailed discussion of this specific task and its relative sensitivity compared to more traditional dual-task paradigms, see Picou and Ricketts (2014a).

Monosyllable words (adapted from commercially available word lists) used during the primary task were spoken by a female talker and were recorded in a professional studio. Words were presented at equivalent root-mean-square levels. Eight lists of 60 words were counterbalanced across and within participants to obviate order effects. Previous work suggested that these lists are approximately equally intelligible. Although not commercially available, these stimuli have been used in other investigations of listening effort (Picou et al., 2014; Picou, Gordon, & Ricketts, 2016; Picou & Ricketts, 2014a; Picou, Ricketts, & Hornsby, 2013). Participants' verbal word recognition responses were manually scored by the experimenter.

During testing, words were presented at 65 dBA, as measured at the height of a typical participant's ear. Words were presented in the presence of four-talker babble. The four talkers were women reading passages from the Connected Speech Test (Cox, Alexander, & Gilmore, 1987; Cox, Alexander, Gilmore, & Pusakulich, 1988). The recordings were edited so that all sentences had the same root-mean-square level. This babble noise has been used previously in tasks of listening effort (Picou et al., 2013, 2014; Picou & Ricketts, 2014a). Two SNRs (+4 and +7 dB) were used for testing.

Subjective Ratings

Subjective ratings were acquired in each test condition. Participants answered three questions on a scale of 0 to 10, where 0 meant *very* and 10 meant *not at all.* The three verbatim questions were as follows:

1. How hard did you work to understand what was said? Remember, this is different than how many words you got right. For example, you could get all the words right but have to work very hard to do it.
2. How likely would you be to try to do something else to improve the situation (e.g., move to a quiet room, ask the speaker to speak louder)?
3. How tired of listening do you feel?

These questions are referred to herein as *work, control,* and *tiredness,* respectively. These questions are a subset of those previously used by Picou and Ricketts (2014b).

Test Environments

Participants completed testing in two test environments: a double-walled, sound-attenuating booth and a reverberant room. In the sound booth (4 × 4.3 × 2.7 m, T30 < 100 ms), Presentation software (Neurobehavioral Systems Version 14.2) delivered the speech stimuli via custom programming on the experimenter's computer. From the computer, the speech was routed through a Madsen Orbital audiometer (Madsen Orbiter 922 v2, Schaumburg, IL), used to adjust the intensity of speech stimuli, and finally to a loudspeaker (Tannoy System 600, Coatbridge, Scotland) located 1 m directly in front of the listener. Background noise was presented from the experimenter's computer using Adobe Audition CS5.5 (San Jose, CA) and routed through a sound card (Digital Audio Echo Layla 3G, Layla Echo, Santa Barbara, CA) to a multichannel amplifier (Russound DPA-6.12, Newmarket, NH). The amplifier output was then routed to four loudspeakers (Definitive Technologies, BP-2x, Definitive BP-2X, Owings Mills, MD) placed 1.5 m from the participant at equal eccentricities (45°, 135°, 225°, and 315°).

The reverberant room (5.5 × 6.5 × 2.25 m) was modified using carpeting and wall- and ceiling-mounted acoustic blankets to achieve a moderate reverberation time (T30 = 475 ms). Speech stimuli were delivered using Presentation software from the experimenter's computer, through a programmable attenuator (TDT System 3 PA5, Alachua, FL) for level control, and finally to a loudspeaker (Tannoy System 600A) located 1 m directly in front of the listener. Background noise was presented using Adobe Audition CS5.5 and routed through a sound card (Echo Layla 3G) to a multichannel amplifier (Crown CTs 8200, Elkhart, IN) and finally to four powered loudspeakers (Tannoy System 600). The four noise loudspeakers were positioned approximately 3.5 m from the participant at equal eccentricities (45°, 135°, 225°, and 315°). The placement of the noise loudspeakers in the reverberant room was intended to maximize the effects of reverberation with regard to noise reflection and diffusion. Placing loudspeakers well within the critical distance in reverberant rooms minimizes the negative effects of reverberation (Ricketts & Hornsby, 2003). Because of the low reverberation, increasing the loudspeaker distance in the sound booth would not be expected to affect sound diffusion. Although it may have been preferred to have all noise loudspeakers placed 3.5 m from the participant for the sake of symmetry, it was not possible because of the limited dimensions of the sound booth.

Procedures

Participants completed testing over the course of three laboratory visits. During the first visit, consent was obtained, hearing thresholds were acquired, tympanometry was completed, and the hearing aids were fitted as described previously. During the second and third visits, participants completed dual-task testing in each of the two test environments. Testing during a visit was completed in only one of the environments. Prior to testing each day, participants practiced the dual-task paradigm three times. During the first practice, participants were instructed only to perform the secondary task (press the button if the word could be used as a noun). During the second and third practices, participants performed both primary and secondary tasks in quiet and in noise, respectively. The purpose of the practice lists was to familiarize participants with the procedures and to reduce potential learning effects.

Immediately following the practice sessions but prior to data collection during a test visit, a room-specific baseline measure was recorded by evaluating a participant's response time during the secondary task alone. After the three practice sessions and the baseline measure, data collection commenced, during which participants always performed both the primary and the secondary tasks. Participants were tested in two SNRs in the three hearing aid programs two times for a total of 12 conditions in each test environment (2 SNRs × 3 hearing aid programs × 2 repetitions). To further reduce potential learning effects, test order across the 12 conditions was counterbalanced but blocked so that testing was completed for the first repetition of all conditions before commencing the second repetition. Order of test environment was also counterbalanced so that half of the participants were tested in the reverberant environment first.

Data Analysis

Data from each of the repetitions were averaged to provide 12 scores for each of five dependent variables (word recognition performance, response times, subjective ratings of work, subjective ratings of control, and subjective ratings of tiredness). Before analysis, the data were transformed as follows. First, the word recognition scores were transformed to rationalized arcsine units to normalize the variance at the extremes (Studebaker, 1985). Second, the room-specific baseline measures were subtracted from the mean response times in each condition to account for any potential system timing differences between test environments. Third, initial analysis of the subjective ratings revealed nonnormal distributions. Therefore, the subjective ratings were transformed by calculating the square root of the raw scores. As a result, the distribution of subjective ratings became normally distributed (Shapiro-Wilk $p > .05$).

After transformation, all data met the assumptions necessary for parametric statistical analysis. As a result, data were analyzed parametrically using separate repeated measures analysis of variance (ANOVA). In all cases, there were three within-subject factors: reverberation (T30 < 100 ms, T30 = 475 ms), SNR (+4, +7), and microphone (omnidirectional, traditional directional, bilateral beamformer). Whenever there was a significant main effect of microphone, the effect was further explored using multiple pairwise comparisons while controlling for familywise error rates with Bonferroni adjustments (Dunn, 1961). Two between-subjects factors—hearing aid experience (new user, > 6 months of experience) and age (≤ 60 years, > 60 years)—were also included initially; results revealed no significant main effects or interactions with the between-subjects factors. In addition, the statistical results from the other factors (reverberation, SNR, microphone) were unaffected by the exclusion of the between-subjects factors. Therefore, only the analyses without the between-subjects factors are reported.

Results

Word Recognition

Mean word recognition performance as a function of condition is displayed in Figure 2. Analysis results revealed a significant main effect of SNR, $F(1, 15) = 136.05$, $p < .001$, $\eta_p^2 = .90$; and a significant main effect of microphone, $F(2, 14) = 41.53$, $p < .001$, $\eta_p^2 = .86$. Results of follow-up testing revealed that performance was worse with omnidirectional compared with traditional directional processing ($p < .001$; Cohen's $d = 0.55$) and bilateral beamformer ($p <.001$; Cohen's $d = 0.51$). However, the two types of directional processing were not significantly different from each other ($p = 1.00$; Cohen's $d = 0.00$). There was no significant main effect of reverberation, and there were no significant interactions. These results suggest that improving the SNR improved word recognition performance, whereas reverberation had no effect. The results also suggest that both types of directional microphones improved word recognition equally.

Response Times

Mean response times as a function of condition are displayed in Figure 3. Statistical analysis revealed a significant main effect of SNR, $F(1, 15) = 5.17$, $p < .01$, $\eta_p^2 = .26$; and a significant main effect of microphone, $F(2, 14) = 6.05$, $p < .05$, $\eta_p^2 = .46$. In addition, there was a significant Reverberation × Microphone interaction, $F(2, 14) = 4.25$, $p < .05$, $\eta_p^2 = .38$. The main effect of reverberation and the other interactions were not significant. These results suggest that there was no effect of reverberation on response times, but improving the SNR improved response times. In addition, directional processing affected response times, but the effect varied as a function of reverberation.

To explore the Reverberation × Microphone interaction, separate follow-up ANOVAs, both with two within-subject factors (SNR, microphone), were conducted on response times for each level of reverberation. Results in the low-reverberation condition revealed no significant main effects or interactions. Cohen's d values for the effect of microphone technology were 0.05 and 0.04 for benefits of directional and beamformer microphone modes relative to the omnidirectional setting, respectively. These very small effect sizes confirm that response times were similar, regardless of microphone condition in low reverberation.

Figure 2. Mean word recognition performance in rationalized arcsine units (RAU) as a function of reverberation (low reverberation indicates T30 < 100 ms; moderate reverberation indicates T30 = 475 ms) for both signal-to-noise ratios. Performance is displayed for omnidirectional (white bars), traditional directional (light gray bars), and bilateral beamformer (dark gray bars) processing. Error bars represent ±1 *SD* from the mean.

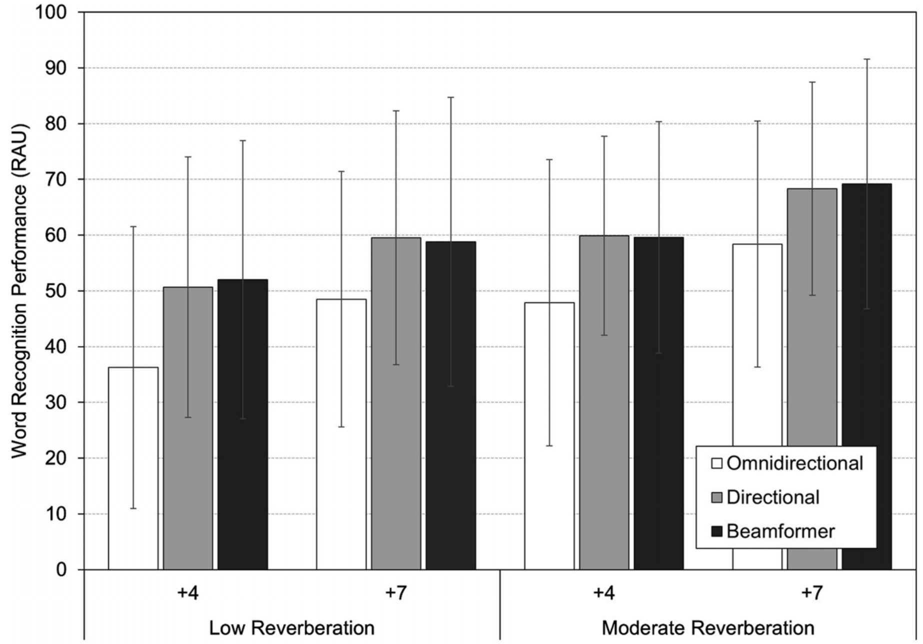
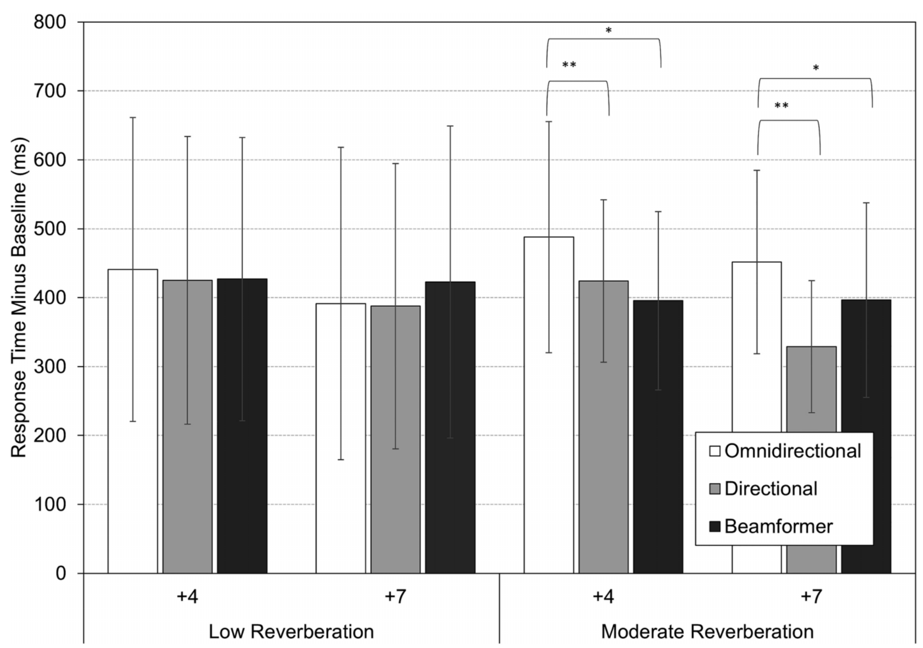


Figure 3. Mean response times (minus baseline) as a function of reverberation (low reverberation indicates T30 < 100 ms; moderate reverberation indicates T30 = 475 ms) for both signal-to-noise ratios. Response times are displayed for omnidirectional (white bars), traditional directional (light gray bars), and bilateral beamformer (dark gray bars) processing. Error bars represent ±1 *SD* from the mean. *Significant differences at $p < .05$. **Significant differences at $p < .01$.



Results in the moderately reverberant condition revealed a significant main effect of microphone, $F(2, 14) = 8.795$, $p < .001$, $\eta_p^2 = .56$. Further follow-up analyses were conducted using multiple pairwise comparisons and controlling for familywise error rates using Bonferroni adjustments. Results revealed that response times were significantly slower with omnidirectional microphones compared with traditional directional processing ($p < .01$; Cohen's $d = 0.80$) and the bilateral beamformer ($p < .05$; Cohen's $d = 0.61$). However, performance with traditional directional processing and bilateral beamformer was not significantly different ($p = 1.0$; Cohen's $d = 0.19$). These results suggest that directional processing did not affect listening effort in low reverberation, but both types of directional processing (traditional and beamformer) improved listening effort in moderate reverberation. However, there was no additional advantage (or cost) of the more advanced directional processing (bilateral beamformer) relative to the traditional directional processing.

Subjective Ratings

Mean subjective ratings as a function of condition are displayed in Table 1, and the results of the ANOVAs are displayed in Table 2. The three subjective ratings (work, control, and tiredness) showed significant effects of SNR and microphone. Improving the SNR and using directional microphones improved subjective ratings for all three questions. The bilateral beamformer did not offer additional subjective benefits (or costs) relative to the traditional directional microphone and in one case (ratings of control) did not elicit subjective ratings that were significantly different from those provided in omnidirectional conditions.

Relationship Between Outcomes

A second purpose of this study was to investigate the relationships between word recognition performance (rationalized arcsine units), objective listening effort (response times in milliseconds), and subjective ratings. To accomplish this, data were collapsed across condition (reverberation, SNR, directional processing). Internal consistency analysis revealed that responses to the three subjective questions had acceptable internal consistency (Cronbach's $\alpha = 0.712$; Nunnally & Bernstein, 1994; Streiner, 2003). Partial correlations between the outcome measures were calculated while controlling for the effects of age. Table 3 displays the results of these analyses. Results revealed that all of the variables were significantly related. As word recognition performance improved, response times were faster and subjective ratings of work, desire to control, and tiredness improved.

To analyze the difference between the correlations between recognition ratings and response time ratings, multiple pairwise comparisons were made between the correlation coefficients for all three questions. Results revealed that the subjective ratings of work were more strongly correlated with word recognition than with response times, $t(189) = 2.07$, $p < .05$, $r = .15$. Subjective ratings of tiredness were also more strongly correlated with word recognition than with response times, $t(189) = 3.85$, $p < .01$, $r = .27$. On the other hand, subjective ratings of control were not more strongly correlated with response times than word recognition, $t(189) = -3.22$, $p > .01$, $r = .23$. In total, these results suggest that the subjective ratings of work and tiredness were more closely related to word recognition performance than to objective listening effort, whereas subjective ratings of control were more strongly related to objective listening effort than word recognition.

Table 1. Mean (standard deviation) transformed subjective ratings as a function of condition for each question.

	Low reverberation		Moderate reverberation	
Variable	**+4**	**+7**	**+4**	**+7**
Work				
Omnidirectional	0.96 (0.6)	1.17 (0.7)	1.16 (0.7)	1.63 (0.9)
Directional	1.30 (0.7)	1.47 (0.7)	1.54 (0.6)	1.79 (0.8)
Beamformer	1.08 (0.9)	1.41 (0.7)	1.51 (0.8)	1.82 (0.7)
Control				
Omnidirectional	1.22 (1.0)	1.31 (1.0)	1.19 (0.7)	1.47 (0.8)
Directional	1.28 (1.0)	1.41 (1.0)	1.44 (0.8)	1.64 (0.8)
Beamformer	1.30 (1.0)	1.38 (1.0)	1.53 (0.8)	1.45 (0.8)
Tiredness				
Omnidirectional	1.74 (0.9)	1.88 (0.9)	2.05 (0.9)	2.33 (0.7)
Directional	1.91 (0.9)	2.04 (0.8)	2.18 (0.8)	2.50 (0.5)
Beamformer	1.90 (0.9)	1.98 (0.9)	2.26 (0.7)	2.39 (0.5)

Note. Higher scores indicate less perceived work, desire to control, and tiredness.

Discussion

Directional Processing

One of the goals of this study was to evaluate the potential effects of directional processing (traditional directional and bilateral beamformer) on word recognition performance and listening effort in two SNRs and two levels of reverberation. The results revealed that both types of directional processing improved word recognition in noise (see Figure 2). These results are consistent with a large body of literature demonstrating speech recognition benefits in the laboratory with spatially separated speech and noise (Hawkins & Yacullo, 1984; Madison & Hawkins, 1983; Ricketts, 2000; Ricketts & Hornsby, 2003).

However, the results of the present study do not demonstrate additional advantage of the bilateral beamformer for word recognition relative to the traditional directional microphone. These findings are in contrast to previous studies (e.g., Best et al., 2015; Picou et al., 2014). The reason for the discrepancy may be related to a number of factors, including use of words as stimuli, reverberation times, and participant characteristics.

First, monosyllabic words were used as speech stimuli, whereas previous investigations demonstrating bilateral beamformer benefits in realistic listening situations used

Table 2. Results of analyses of variance with three within-subject factors (reverberation, signal-to-noise ratio, microphone) and multiple pairwise comparisons to follow up significant main effects, if applicable.

Variable	Reverberation	Signal-to-noise ratio	Microphone
Work	$F(1, 15) = 3.25$ $p = .09$ $\eta_p^2 = .18$	$F(1, 15) = 26.68$[a] $p < .001$[a] $\eta_p^2 = .64$[a]	$F(2, 14) = 10.44$[a] $p < .01$[a] $\eta_p^2 = .60$[a] Omnidirectional < directional ($p < .01$)[a] Omnidirectional < beamformer ($p < .01$)[a] Directional = beamformer ($p = .45$)
Control	$F(1, 15) = 0.25$ $p = .63$ $\eta_p^2 = .17$	$F(1, 15) = 4.55$[a] $p < .05$[a] $\eta_p^2 = .23$[a]	$F(2, 14) = 5.54$[a] $p < .05$[a] $\eta_p^2 = .442$[a] Omnidirectional < directional ($p < .05$)[a] Omnidirectional = beamformer ($p = .09$) Directional = beamformer ($p = 1.0$)
Tiredness	$F(1, 15) = 3.68$ $p = .79$ $\eta_p^2 = .20$	$F(1, 15) = 8.22$[a] $p < .05$[a] $\eta_p^2 = .35$[a]	$F(2, 14) = 4.66$[a] $p < .05$[a] $\eta_p^2 = .40$[a] Omnidirectional < directional ($p < .05$)[a] Omnidirectional < beamformer ($p < .05$)[a] Directional = beamformer ($p = .95$)

[a]Effect is significant.

sentence stimuli (Best et al., 2015; Picou et al., 2014). The performance-intensity function for words is considerably shallower than for sentences, potentially rendering them less sensitive to true differences in speech recognition (e.g., Boothroyd, 2008; Davis & Silverman, 1960). In the present study, the average directivity improvement from omnidirectional to traditional directional was approximately 5 dB, whereas the beamformer provided only an additional 2 dB of directivity. It is possible that this additional 2 dB was not sufficient to adequately affect word recognition performance.

Second, Picou et al. (2014) previously demonstrated an interaction between bilateral beamformer benefit and reverberation time, with significant additional benefits of a bilateral beamformer evident only in moderate reverberation (T30 = 675 ms). Two levels of reverberation—low and moderate—were used in the present study. However, the moderate reverberation time was slightly less than one previously used (T30 = 475 instead of 675). Although the difference is relatively small and both levels of reverberation can be considered moderate in degree, it is possible that additional beamformer benefit would have been evident if a more reverberant test environment had been used.

Third, previous investigations have suggested that benefit from bilateral beamformers can be related to inherent listener characteristics. For example, Best et al. (2015) reported significant simple correlations between age and pure-tone averages, suggesting that older adults and those with less hearing loss might be less likely to benefit from beamforming. Perhaps if the present study were replicated with younger listeners with more hearing loss, the beamformer would have provided additional word recognition benefit.

In addition to directional benefit for word recognition, the results of the present study suggest that directional microphones can improve objective listening effort, as indicated by faster response times during the dual task (see Figure 3). This finding is consistent with the ELU model because the directional technology improves the SNR and thus facilitates a match between perceived language and long-term memory stores. The results of this study suggest that perhaps the previously reported nonsignificant benefits of directional technologies for listening effort (e.g., Hornsby, 2013; Picou et al., 2014; Wu et al., 2014) were the result of methodological limitations. These limitations may have been

Table 3. Pearson correlations between study outcome measures (word recognition performance, response times, and subjective ratings on each of the three questions), controlling for the effects of age.

Measure	Word recognition	Response times	Ratings of work	Ratings of control	Ratings of tiredness
Word recognition		−.25 (<.010)	.49 (<.001)	.44 (<.001)	.54 (<.001)
Response time			−.32 (<.001)	−.59 (<.001)	−.33 (<.001)
Ratings of work				.70 (<.001)	.40 (<.001)
Ratings of control					.40 (<.001)
Ratings of tiredness					

Note. Numbers in parentheses are two-tailed significance values.

the use of an insensitive paradigm (Picou et al., 2014), noise levels that were too low to activate directional processing (Hornsby, 2013), or listening situations that were too challenging (Wu et al., 2014). In the present study, attempts were made to account for these methodological limitations, and the result was a significant benefit of directional processing for listening effort. When present, the benefits of directional technology for improving listening effort resulted in medium to large effect sizes (Cohen's d = 0.61 and 0.80 for directional and beamformer settings, respectively).

Also of note was the finding that the magnitude of objective listening effort was similar for traditional directional processing and the bilateral beamformer (20-ms difference; Cohen's d = 0.18). This finding suggests that, although the bilateral beamformer investigated in the present study has previously been shown to distort natural interaural cues (Picou et al., 2014), this disruption does not appear to increase listening effort. Indeed, even with this spatial distortion, listening effort benefit was found relative to the omnidirectional setting.

Reverberation

The aforementioned benefits of directional processing for listening effort, unlike word recognition performance, varied as a function of reverberation. Two levels of reverberation were used because previous findings have suggested an interaction between reverberation and benefit with traditional directional microphones (Ricketts & Hornsby, 2003) and the bilateral beamformer (Picou et al., 2014). Results indicated that the benefits of directional processing for listening effort were present only in the room with moderate reverberation (T30 = 475 ms). These results demonstrate that the effects of directional processing on listening effort may be measurable only in rooms with some reverberation, suggesting that listening effort results obtained in an audiometric test booth may not generalize to rooms with more reverberation.

When combined with previous findings (Picou et al., 2014), these results suggest that benefits for bilateral beamformers may be relegated to more difficult and complex listening environments such as those that include higher levels of reverberation. However, the two test environments used in this investigation varied not only by reverberation but also by noise loudspeaker distance and room size. The noise loudspeakers were 3.5 m away from the participant in moderate reverberation and 1.5 m away from the participant in low reverberation, although loudspeakers were always outside the critical distance. Likewise, the two test environment room sizes were different. The low-reverberation environment was 46 m^3, whereas the moderate-reverberation room was 80 m^3. It is not clear what effect, if any, noise loudspeaker distance or room size had on the results of the present study.

Despite the significant interaction between reverberation and directional benefit for listening effort, there was no main effect of reverberation for either word recognition or response times. The nonsignificant effect is somewhat surprising, given the well-documented consequences of reverberation on speech recognition, particularly for older adults and those with hearing loss (Duquesnoy & Plomp, 1980; Finitzo-Hieber & Tillman, 1978; Harris & Reitz, 1985; Humes & Roberts, 1990; Nábělek & Mason, 1981; Nábělek & Pickett, 1974).

On the other hand, the nonsignificant effect of reverberation on objective listening effort is consistent with previous results for listeners with typical hearing. Picou et al. (2016) found no significant effects of reverberation on objective listening effort over the same range of reverberation times as in the present study. However, both the present findings and those of Picou et al. (2016) are somewhat surprising given the documented changes in subjective listening effort with increases in reverberation (e.g., Rennies et al., 2014; Sato & Bradley, 2008). It is likely that the relatively small range of reverberation times (T30 < 100 ms to T30 = 475 ms), coupled with the use of monosyllabic words as speech stimuli, could have obscured effects of reverberation. Future studies are warranted to further explore the main effects of reverberation on listening effort for adults with hearing loss.

Subjective Ratings

The second goal of this study was to evaluate the relationship between subjective and objective indices of listening effort and to investigate whether manipulating the subjective questions could change the relationship between the two measures. As a result, three questions were asked after each test condition. These questions were related to participants' perceptions of work, control, and tiredness. In general, the results of the analysis of subjective data are consistent with the word recognition data (Tables 1 and 2); favorable SNRs and directional processing improved subjective ratings. The bilateral beamformer did not further improve ratings. This pattern of results was also consistent with the response times in moderate reverberation but not in low reverberation. Response times in low reverberation were not consistently affected by directional processing. In total, these results would suggest that the subjective questions were more closely related to word recognition performance than response times.

It was also of interest to evaluate the relationships between word recognition and subjective ratings and between response times and subjective ratings. Correlation analysis revealed that subjective ratings were significantly related to word recognition performance and response times. However, except for the question about control, the relationships between word recognition and subjective ratings were stronger than the relationships between response times and subjective ratings. For the question about control, ratings were more strongly correlated with response times than word recognition. In total, these results suggest that the question about control may be a viable option for eliciting subjective ratings that are more closely related to objective listening effort than the other subjective ratings used in the current study.

Study Limitations

Although the findings regarding the effects of directional processing and reverberation have implications for clinical practice as well as future research, some methodological choices may limit the study generalizability and warrant further investigation. First, the sample size was relatively small (16 participants). It is possible that some of the insignificant benefits of directional microphones reported in the present study are related to insufficient statistical power.

Second, the participants were relatively heterogeneous, reflecting a range of ages (23–79 years). Previous investigators have reported that age can increase listening effort when listeners have typical (e.g., Gosselin & Gagné, 2011) or impaired (e.g., Tun, McCoy, & Wingfield, 2009) hearing. In addition, participants had a range of hearing aid experience; seven participants had no experience, and nine had 6 months to 19 years of experience (M = 8.2 years). Because experience with particular hearing aid settings has been shown to influence listening effort (e.g., Rudner, Foo, Sundewall-Thorén, Lunner, & Rönnberg, 2008), it is not clear to what extent previous experience might interact with microphone benefit. Although attempts were made to statistically control for the possible effects of age and hearing aid experience in the present study, future studies are warranted to fully explore the potential interactions between age, hearing aid experience, and microphone benefit for listening effort.

Third, the findings are limited to the SNRs and reverberation levels studied. It is possible that longer reverberation times or better SNRs could reveal a different pattern of directional microphone benefits. Consistent with this, Wu et al. (2014) predicted that directional benefits for listening effort would be present only in specific segments of the performance-intensity function. Perhaps if participants' overall performance was better, the change in microphone technology might have had a larger effect on listening effort. On the other hand, one might predict that a poorer SNR might reveal more beamformer benefits when the task is more difficult. Future studies are warranted to fully explore directional and beamformer benefits across a full range of reverberation times, SNRs, and performances.

Last, the findings related to the subjective questions may be limited in generalizability as a result of question presentation. Participants always answered the questions in the same order (work, control, tired). Furthermore, participants may have responded differently to each question because they were always presented together. Future work is warranted to investigate whether the relationships between word recognition, objective effort, and subjective effort are maintained with alternative presentation orders or when the questions are presented in isolation rather than in combination.

Conclusions

The purposes of this study were (a) to evaluate the potential for directional processing to affect listening effort and (b) to investigate relationships between subjective ratings and objective effort. Results revealed that directional processing improved listening effort, although the benefit was found only in the test environment with moderate reverberation. This suggests that results of listening effort studies conducted in audiometric sound booths with little reverberation may not generalize to more reverberant environments. In addition, the bilateral beamformer did not offer additional advantage or decrement compared to the traditional directional microphone processing, but this might be due to the monosyllabic words used as speech stimuli or the relatively moderate degree of hearing loss of study participants. Last, changing the question designed to elicit subjective ratings of effort did alter the relationship between subjective and objective effort. Subjective indices of listening effort asking about work or tiredness were more highly correlated with word recognition performance than objective listening effort. However, asking participants how likely they were to exercise control to improve the situation resulted in ratings that were more strongly correlated with objective listening effort than word recognition performance. These results suggest that this type of question might be a potential option for eliciting subjective ratings that are significantly related to objective listening effort in future studies.

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