Multitasking with typical use of hearing aid noise reduction in older listeners

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Abstract

Objective: Older hearing-impaired adults typically experience difficulties understanding speech in noise. Most hearing aids address this issue using digital noise reduction. While noise reduction does not necessarily improve speech recognition, it may reduce the resources required to process the speech signal. Those available resources may, in turn, aid the ability to perform another task while listening to speech (i.e., multitasking). This study examined to what extent changing the strength of digital noise reduction in hearing aids affects the ability to multitask. *Design:* Multitasking was measured using a dual-task paradigm, combining a speech recognition task and a visual monitoring task. The speech recognition task involved sentence recognition in the presence of six-talker babble at signal-to-noise ratios (SNRs) of 2 and 7 dB. Participants were fit with commercially-available hearing aids programmed under three noise reduction settings: off, mild, strong. *Study sample:* 18 hearing-impaired older adults. *Results:* There were no effects of noise reduction on the ability to multitask, or on the ability to recognize speech in noise. *Conclusions:* Adjustment of noise reduction settings in the clinic may not invariably improve performance for some tasks.

List of abbreviations

AIC Akaike Information Criterion

NR noise reduction

SNR signal-to-noise ratio

Introduction

Difficulty understanding speech in noise is one of the most frequent complaints of hearing aid wearers (Kochkin, 2011). To address this problem, most hearing aids employ some type of digital noise reduction (NR). The purpose of NR is to suppress background noise, thereby enhancing the target speech signal. While an early goal of NR was to improve recognition of speech in noise (Sammeth & Ochs, 1991), it is now recognized that improved speech recognition should not be expected (McCreery, Venediktov, Coleman, & Leech, 2012; Bentler, Wu, Kettel, & Hurtig, 2008). However, NR may have other benefits. Among the noted improvements are greater noise tolerance (Wu & Stangl, 2013; Bentler et al., 2008), greater word recall (Ng, Rudner, Lunner, Pedersen, & Rönnberg, 2013), improved sound quality (Ricketts & Hornsby, 2005), and reduced listening effort (compared to amplification without NR; e.g., Brons, Houben, & Dreschler, 2012; Sarampalis et al., 2009, but see e.g. Desjardins, 2016; Brons et al., 2014). This paper addresses the question whether NR might also provide some benefits for older hearing-impaired listeners' in terms of their ability to perform a secondary task while trying to understand speech in the presence of background noise (i.e. multitasking). Of particular interest is the effect of varying the strength of NR on the ability to multitask.

Multitasking during speech perception is common in everyday life (e.g., driving while having a conversation, listening to a podcast while buying groceries, browsing the internet while attending a lecture). However, this can be challenging as people only have a finite pool of cognitive resources that can be allocated among tasks (Kahneman, 1973). More limited resources and/or higher task demands will exhaust resources, resulting in poorer performance. First, consider listening under favourable conditions, with a clear, distinct talker, no background noise, and where the listener is a native speaker and has normal or near-normal

hearing. It has been theorized that under such conditions, acoustic information will be rapidly and automatically matched to stored lexical representations, requiring little cognitive effort (Rönnberg et al., 2013). As understanding speech under such favourable conditions requires relatively little cognitive effort, sufficient cognitive resources are typically available to adequately perform a competing task. Next, consider listening under difficult conditions, with an indistinct talker, background noise, and where the listener has hearing loss. Under such conditions, many acoustic cues will be masked or inaudible. The sparse remaining cues will require the listener to focus more closely on the available information and/or use top-down processing to “fill in” missed information. The increased task demands mean that fewer cognitive resources are available for other tasks that need to be performed simultaneously. Moreover, performance on the secondary task may suffer even if the participant has sufficient resources to devote to the primary task. Hence, a paradigm that taps into the ability to multitask, such as a dual-task paradigm, may be more sensitive to subtle forms of stimulus degradation - or enhancement-- than direct measures that assess speech recognition.

Dual-task paradigms rely on the ability to multitask and can be used to quantify the allocation of cognitive resources during speech perception. In such a dual-task paradigm, participants perform a speech perception task and simultaneously perform a secondary task that competes for cognitive resources. Several studies have used a dual-task paradigm to examine the potential benefits of NR (e.g. Sarampalis et al., 2009; Neher, Grimm, & Hohmann, 2014; Desjardins & Doherty, 2014; Desjardins, 2016). However, these studies were interpreted within the context of listening effort (i.e. “the deliberate allocation of mental resources to overcome obstacles in goal pursuit when carrying out a [listening] task”; Pichora-Fuller et al., 2016). Performance on the secondary task was quantified only during the periods in the speech recognition task when participants were actually listening to speech. In the dual-task used in the current study, however, performance on the secondary task was quantified not only while

the sentences were presented, but also while the participant was repeating the sentence, and during periods of silence. Thus, the task captured not just listening effort, but also repetition effort, and recovery. As such, it is perhaps best interpreted as a task simply tapping into the ability to divide cognitive resources across multiple tasks (i.e. multitasking). Despite these task differences, there is also a striking similarity between the task used in the current study and the dual-task paradigms reported in the literature used to study the effects of NR on listening effort. In both cases, the participants need to divide their cognitive resources across multiple tasks (i.e., recognizing speech while performing a competing task). We will therefore interpret these studies more generally within the context of multitasking and may use the terms listening effort and multitasking somewhat interchangeably.

Several studies using a dual-task paradigm have found that performance improves with NR (e.g., Sarampalis et al., 2009; Desjardins & Doherty, 2014, Neher, Grimm, & Hohmann, 2014). However, the results are most positive in simulation studies conducted with listeners who have normal or near-normal hearing (Sarampalis et al., 2009; Neher, Grimm, & Hohmann, 2014). Such studies have the advantage of clear acoustic effects where the simulation is calibrated such that noise is certain to have been reduced and the signal-to-noise ratio (SNR) improved, presented to listeners who are capable of utilizing enhanced speech information. As a group, those studies convincingly demonstrate that digital noise reduction can reduce listening effort or improve the ability to multitask, even when it does not improve speech intelligibility.

Understanding multitasking relative to hearing aids for listeners with hearing loss is more complicated. It is difficult to anticipate how much noise might be reduced in an individual hearing aid fitting. The effect of noise reduction on multitasking may be small in some listening environments (Sorensen & Jespersen, 2015) and will also depend on the specific algorithm used to reduce noise (Bentler & Chiou, 2006; Sorensen & Jespersen, 2015).

The extent of the effect may also depend on the parameter settings of the hearing aid. A recent survey (Anderson, Arehart, Souza, 2017) suggests that approximately 40% of audiologists modify the manufacturer's default noise suppression parameters (i.e., change NR strength). Clinicians might reasonably expect that increasing the strength of the digital noise reduction setting will remove more noise, result in less effortful listening, and improve an individual's ability to perform two tasks simultaneously. However, there may be a trade-off in many noise reduction algorithms such that as more noise components are removed, there is greater potential for speech components to be removed along with the noise (Arehart, Souza, Kates, Lunner, & Pedersen, 2015; Brons et al., 2012). That removal of speech information can result in degraded speech. Because listening to degraded speech is more effortful (Ward et al., 2017; Winn, Edwards, & Litovsky, 2015), it is also possible that stronger forms of NR which result in speech degradation will be more effortful than unprocessed speech, even if more noise is removed. Stronger forms of NR may thus result in fewer cognitive resources being available for any competing tasks. In support of this idea, a recent study showed that listeners who preferred weaker NR strength were better able to detect, and therefore more sensitive to, distortions in a speech signal (Neher et al., 2015). From a clinical perspective, then, there is a need to further explore the benefits of digital noise suppression in typical hearing aid wearers, as well as to understand the effects of noise reduction strength.

Several studies have examined dual-task performance in older adults fit with hearing aids. In each case, performance was measured for the same hearing aid programmed with and without (strong) NR. Some research found no reduction in listening effort with NR (Desjardins, 2016); other research by the same group found reduced listening effort only under more challenging listening conditions (i.e., when speech reception thresholds were tracked at 50% correct; Desjardins & Doherty, 2014). Based on previous work, it seems reasonable to say that digital noise reduction *might* improve the ability to multitask, but the exact circumstances

under which this occurs need to be more clearly defined. Because the existing work compared a single NR setting (typically strong noise reduction) to a control condition with no NR, it is unclear whether adjustments in the strength of the noise reduction will affect listening effort or the ability to multitask. For the present study, the question of interest is to what extent will the ability to perform two tasks simultaneously change under clinical conditions where the hearing aid is individually adjusted for the patient and where the strength of noise reduction is varied?

Methods

Participants

Twenty-one older adults enrolled in the study. Three of the participants were later excluded. Of those, two participants were excluded because they could not perform the task and a third participant was excluded due to technical issues during the test session. Data are presented here for the remaining 18 older adults aged 62 – 88 years (mean age 74 years, 11 women) with mild-to-moderate hearing loss (see Fig. 1). Their hearing loss was sensorineural, as indicated by air-bone gaps ≤ 10 dB at octave frequencies from 0.5 – 4 kHz¹, and symmetrical (pure-tone average threshold difference across the ears ≤ 15 dB). Four of the participants were hearing aid users. All participants were native speakers of American English and received a score of 22 or better on the Montreal Cognitive Assessment (Nasreddine et al., 2005). None of the participants reported any neurological or language disorders. All study procedures were approved by the Northwestern University Institutional Review Board (reference number

¹ One participant with a history of tympanic membrane perforation had an air-bone gap of 15 dB at 1 kHz.

STU00061167) and all participants completed an informed consent process and were paid for their participation.

Figure 1: Individual audiograms for the left and right ear. The shaded area represents the mean $\pm$ 1 sd.

Hearing aid fitting

Participants were fit with a pair of commercially available behind-the-ear digital hearing aids (frequency range: 100 – 6140 Hz, 17 channels). The hearing aids were connected via an ear hook to disposable unvented foam ear tips (Westone E-A-RTEMP Eartip, 13A standard).

Hearing aids were fit to the National Acoustics Laboratories Nonlinear 2 (NAL-NL2) prescription targets. Real-ear hearing aid verification was conducted using the Speechmap

feature of the Audioscan Verifit system (Dorchester, ON, Canada), which makes use of speech signals to verify whether the hearing aid provides the desired level of amplification. Responses to the Verifit Speech Test Signal (the “carrot passage”) presented at 50 and 70 dB SPL were matched to target within ± 5 dB from .25-4 kHz (except when the target was below the audiometric threshold, which was the case for the majority of the participants at 4 kHz).

A custom program was created in which the microphone directionality was set to omnidirectional, wide dynamic range compression speed was set to syllabic (attack time 12 ms, release time 70 ms), and any advanced signal processing apart from digital noise suppression was deactivated (i.e. expansion, frequency compression, and wind noise suppression). Digital feedback suppression was also turned off, except for three participants who experienced feedback that could not be suppressed via acceptable frequency-gain modifications to the hearing aids. In addition, volume control was disabled.

Noise reduction in this product employs a version of spectral subtraction based on Wiener filtering in different frequency bands (Boll, 1979; Appleby & Groth, undated). Maximal gain reduction is specified as 3 dB in the “mild” setting and 10 dB in the “strong” setting (Appleby & Groth, undated), although those values represent gain reduction for a non-speech noise (e.g., not background babble) at 0 dB SNR. Less gain reduction would be expected to occur at more favourable SNRs and/or with different background noises.

In order to examine the effects of the strength of noise reduction on the ability to perform two tasks at once, the hearing aids were either programmed with digital noise reduction turned off, set to mild, or set to strong. All participants completed the experiment with the hearing aids set in all three noise reduction conditions. Conditions were presented in a random order for each participant.

Acoustic measurements of noise reduction

To verify that changing the noise reduction strength in the hearing aids had an effect acoustically, recordings were made of representative stimuli as used in the speech recognition task (an IEEE sentence (Rothauser et al., 1969) in four-talker babble at SNRs of 2 and 7 dB) after they were passed through one of the hearing aids under each of the three noise reduction settings (off, mild, strong). The hearing aid was programmed for a mild sloping hearing loss (standard audiogram N2; Bisgaard, Vlaming, & Dahlquist, 2010).

The recordings were made using a Bruel & Kjaer 2250 sound level meter with a ½ inch pressure-field microphone (4192) connected to a 2cc coupler (type 4946). The hearing aid, which was connected via an ear plug simulator to the sound level meter, was positioned approximately 50 cm in front of the speaker (KEF, iQ1). The stimuli were played at 80 dB SPL. The recordings were made using a sampling rate of 48 kHz and 16 bit resolution.

An inversion technique was used to separate the target sentence and the babble in the recordings (Hagerman & Olofsson, 2004). Figure 2 shows the waveforms and spectra of the extracted target sentence and babble noise for the two SNRs by NR setting (off, mild, strong). The inversion technique allowed for the calculation of the effective SNR of the signals after hearing aid processing. The results indicated that the SNRs improved with increasing noise reduction strength for both input SNRs (2 dB SNR stimulus: off 0.85 dB, mild 1.28 dB, strong 2.17 dB; 7 dB SNR stimulus: off 4.75 dB, mild 5.28 dB, strong 6.13 dB). Increasing the noise reduction strength resulted in an improvement in SNR of approximately 1 dB. The magnitude of noise reduction was similar to that noted in other work (Bentler et al., 2008). Note that the SNRs were typically lower (i.e. poorer) after the signals were passed through the hearing aids, most likely due to wide-dynamic range compression (c.f. Souza, Jenstad, & Boike, 2006; Gustafson et al., 2014).

Figure 2: Waveforms (top) and spectra (bottom) of the speech and noise signals that were extracted from the acoustic hearing aid recordings using an inversion method. Data are plotted for the two SNRs (left: 2 dB, right: 7 dB) by NR setting (blue: off, red: mild, green: strong).

Multitasking

The ability to allocate cognitive resources across different tasks was measured using a dual-task paradigm, combining a speech recognition task (primary) and a visual monitoring task (secondary; Ward et al., 2017; Grieco-Calub, Ward, Brehm, 2017; Wright et al., 2014). Participants performed both tasks in isolation as well as in parallel (dual-task).

Speech recognition (primary task)

Speech recognition was measured using a set of pre-recorded IEEE sentences (Rothauser et al., 1969) produced by a female American English speaker. Each sentence contained five keywords. The sentences were presented in six-talker babble at fixed SNRs of 2 and 7 dB. The SNRs were obtained by keeping the level of the speech fixed and adjusting the level of the masker. A random section of the masker was selected for each stimulus. In order to ensure that the noise reduction algorithm in the hearing aids was engaged by the time the target sentence was presented, the masker started 4 seconds before the onset of the target, a duration which fell within the necessary processor engagement per manufacturer information. The masker continued for an additional 1 second after sentence offset.

The stimuli were presented through an external sound card (M-Audio FireWire Solo) and played via a speaker (Yamaha HS50M) that was positioned at approximately -15 degrees azimuth relative to the participant and at a distance of about 80 cm. The stimuli were played at 70 dB SPL, measured in soundfield (80 cm from the speaker) prior to amplification.

Participants were seated in a double-walled sound-treated booth and were asked to repeat the sentences to the best of their ability. The experimenter scored the number of correctly repeated keywords for each sentence. No feedback was provided. The stimuli were presented with an inter-stimulus interval of 4.5 seconds to give the participants sufficient time to repeat the sentence.

One sentence list, containing ten sentences each, was presented per condition. Since each sentence contained five keywords, this corresponds to a total of 50 keywords per list. Sentence lists were randomized across participants and conditions.

Visual monitoring (secondary task)

In the visual monitoring task, images were displayed sequentially and in a random order on a computer screen. Participants were instructed to press the space bar as quickly as they could when they saw two images in a row that were identical.

The visual stimuli consisted of a set of 64 (720 x 540 pixels, approximately 2.5" x 2.5") pictures of 8 simple shapes (e.g. square, triangle, star) with 8 different colors. The images were displayed using a Mac Mini and the MATLAB PsychToolbox (Mathworks, Natick, MA; Brainard, 1997). Each image was presented for 400 ms, with an interstimulus interval of 400 ms. In total, approximately 150 images were presented during each block, with typically about 11 repeated images (ranging from 9 to 13).

Performance was measured in terms of accuracy (i.e. proportion of correctly identified repeated images) and reaction time (i.e. time between the repeated image and key press). Reaction times were only included for correctly identified repeated images. In addition, if a repeated image was presented during the first 3 seconds of a block, or after 115 seconds (roughly after the last sentence was presented), it was not included. Similarly, reaction times were only counted as a correct response if they occurred 0.3 to 1.5 seconds after a repeated image.

Statistical analyses were performed on the mean reaction times. However, since reaction time data do not follow a normal distribution, the reaction time data were log-transformed before taking the mean. Subsequently, the mean reaction time was converted back to its original scale by taking the exponential.

Dual-task

In addition to the speech recognition and visual monitoring tasks in isolation, participants also performed these two tasks simultaneously. Participants were instructed that

their main goal was to repeat the sentences to the best of their ability. In addition, they were instructed to try to correctly detect as many repeating images as possible.

The visual monitoring task was presented continuously, which means that the repeated image could appear while the auditory stimulus was presented, while the participant was repeating the sentence, and during periods of silence. Thus, the task captures not just listening effort, but also repetition effort, and recovery. As such, it is perhaps best interpreted as a task simply tapping into the ability to divide cognitive resources across multiple tasks (i.e. multitasking). The rationale for including secondary task responses in the silent period following the sentence is that the time course of attention and lexical access extends beyond stimulus presentation (Kahneman, 1973; Wagner et al., 2016).

Speech recognition scores, as well as reaction times and accuracy scores for the visual monitoring task were recorded for each block.

Procedure

Participants received brief training on each task, starting with the visual monitoring task, followed by the speech recognition task, and finally the dual-task. The speech recognition and dual-tasks contained three sentences each, presented at 7 dB SNR. Participants performed these tasks with the hearing aids set to the noise reduction setting of the first test block.

The order of tasks in the experiment proper was as follows (see Fig. 3). Participants first completed the visual monitoring task in isolation. Subsequently, they performed the speech recognition task in isolation, followed by the dual-task. They performed these tasks at both SNRs (2 and 7 dB; randomized across hearing aid settings). This process was repeated for the three different hearing aid settings (noise reduction off, mild, strong). The order of hearing aid settings was randomized across participants. Lastly, in order to be able to assess the effects

of fatigue or practice effects over the course of the experiment, they performed the visual monitoring task in isolation twice more at the end of the test session.

Figure 3: The order of tasks in the experiment, following practice blocks on the visual monitoring and speech recognition tasks in isolation and in parallel (dual-task). The order of noise reduction settings (off, mild, strong) was randomized across participants.

In order to obtain a more reliable measure of the ability to multitask, all measures were obtained twice, at two different sessions. It should be noted, however, that the interval between the two sessions varied across participants (the second session could be on the same day or up to 7 months after the first session). Two participants were unable to return for a second visit and for those individuals, data were only collected at one visit.

Measures of multitasking

The ability to divide cognitive resources across the two tasks was quantified as the change in performance on the visual monitoring task when it was combined with the speech recognition task (i.e. dual-task) compared to when the visual task was performed in isolation ($100 * ((\text{performance in isolation} - \text{dual-task performance}) / \text{performance in isolation})$; Somberg & Salthouse, 1982). These difference scores were normalized with respect to performance on the visual task in isolation to account for individual differences in task performance at baseline (Desjardins & Doherty, 2014). The sign for the normalized reaction times was inverted to make interpretation of the normalized measures easier in that both now go in the same direction.

The higher the normalized scores are, the more the demands of the speech intelligibility task affected the participant's ability to perform the visual monitoring task. In this case, as expected, the participant performed more poorly on the dual-task than on the visual task in isolation.

Results

Data points for a given participant and test block that exceeded the mean by ± 3 sd were considered outliers and removed from the data set. Following this criterion, two reaction times (from two different participants) from the visual monitoring task in isolation were excluded. Furthermore, reaction time data were only included if at least three repeated images were correctly identified for that particular block. Following this criterion, four data points were excluded (two of those data points were from the same participant).

Test-retest reliability

To examine test-retest reliability, intraclass correlation coefficients (ICC; one-way mixed model) were computed in R (version 3.3.0, using the *icc()* function from the *irr* package). ICCs were computed for the accuracy and reaction time scores for the visual task in isolation, the normalized accuracy and reaction time scores for the dual-task, as well as the intelligibility scores pooled across the dual-task and the speech intelligibility task in isolation (see Tables 1 and 2). The ICCs were calculated for the six different conditions (SNR 2 and 7 dB, noise reduction off, mild, strong) separately. Note that the ICCs for the intelligibility measures were computed on the percent correct scores, and not on the binary outcome measure indicating whether a key word in a sentence was correctly repeated or not, to get an indication of the *overall* reliability of the measure.

As a rule of thumb, an $ICC \geq 0.75$ indicates high reliability, whereas an $ICC < 0.4$ indicates poor reliability (Shrout & Fleiss, 1979). The results indicate a high test-retest reliability for the intelligibility scores (ICC range: 0.71 – 0.90) and for the accuracy and reaction time scores for the visual task in isolation (ICC 0.75 and 0.72 respectively). However, performance on the visual task was less consistent across sessions when combined with the speech intelligibility task (i.e. our measure of multitasking). The normalized accuracy scores were generally reliable, with ICCs typically around 0.4, although ranging from 0.12 to 0.90 (see Table 1). The normalized reaction time measure, on the other hand, had very poor test-retest reliability, with ICCs for all conditions < 0.4 (ICC range: -0.54 – 0.38). The results for the normalized reaction time data reported below should therefore be interpreted with caution.

Table 1: Test-retest reliability visual task in isolation

Visual task in isolation accuracy		Visual task in isolation reaction time	
ICC	95% CI	ICC	95% CI
0.75	[0.44, 0.91]	0.72	[0.37, 0.90]

Table 1: Intraclass correlation coefficients (ICCs) and their corresponding 95% confidence intervals for the accuracy and reaction time measures for the visual task in isolation.

Table 2: Test-retest reliability intelligibility and listening effort measures

Condition	Intelligibility (percent correct)		Normalized accuracy		Normalized reaction time	
	ICC	95% CI	ICC	95% CI	ICC	95% CI
SNR 2, NR off	0.84	[0.70, 0.92]	0.90	[0.74, 0.96]	-0.32	[-0.69, 0.18]
SNR 2, NR mild	0.90	[0.80, 0.95]	0.38	[-0.11, 0.73]	0.04	[-0.45, 0.53]
SNR 2, NR strong	0.87	[0.75, 0.93]	0.58	[0.16, 0.83]	0.38	[-0.11, 0.73]
SNR 7, NR off	0.71	[0.49, 0.85]	0.12	[-0.37, 0.57]	0.07	[-0.41, 0.53]
SNR 7, NR mild	0.76	[0.56, 0.87]	0.40	[-0.09, 0.74]	-0.12	[-0.56, 0.38]
SNR 7, NR strong	0.82	[0.67, 0.91]	0.40	[-0.09, 0.74]	-0.54	[-0.81, -0.08]

Table 2: Intraclass correlation coefficients (ICCs) and the corresponding 95% confidence intervals for the intelligibility (percent correct scores – collapsed across performance in isolation and as part of the dual-task), and listening effort measures (normalized accuracy and normalized reaction time).

Speech recognition

Figure 4 shows performance on the speech recognition task (in percent correct) for the three different noise reduction conditions (off, mild, strong) in two different SNRs (2 and 7 dB) when the task was performed in isolation or as part of the dual-task paradigm. It should be noted that while the data are visualised in terms of percent correct scores (for ease of

interpretation), the statistical analyses were instead performed on a binary outcome measure indicating whether a key word in a sentence was correctly repeated or not. Furthermore, even though the percent correct scores shown in Figure 4 indicate a large number of outliers, the data for these test blocks were not excluded. Most of these data points came from two participants who had some of the poorest audiometric thresholds (highest and third highest pure-tone average). It should be noted that excluding the data for these two participants did not change the results of the analyses reported below.

Figure 4: Speech recognition scores, in percent correct, for three noise reduction settings of the hearing aids (off, mild, strong), in two different SNRs (2 and 7 dB), when the task was performed in isolation or in combination with the visual monitoring task. Note that the statistical analyses were not performed on the percent correct scores presented here but on the binary outcome measure indicating whether a key word was correctly repeated or not.

The speech recognition data were analyzed using a logistic mixed-effects model in R (using the *glmer()* function from the *lme4* package). The dependent variable was the correct or incorrect repetition of the key words in each of the sentences. Model comparisons based on the Akaike Information Criterion (AIC) indicated that a model with SNR (categorical variable: 2, 7 dB SNR) and noise reduction (categorical variable: off, mild, strong) as fixed factors and listener and sentence as random factors provided the best fit for the data. Only main effects were tested, since including an interaction term (SNR x NR) did not improve the model fit ($\chi^2 = 1.04$, $p = 0.6$; AIC model with interaction: 13070, AIC model without interaction: 13067). Similarly, a model including paradigm (categorical variable: dual-task, speech recognition in isolation) and/or session did not provide a better fit for the data. Two contrasts were set up to examine the effects of noise reduction *per se* (off vs. mild and strong) and the strength of noise reduction (mild vs. strong).

The results showed a main effect of SNR, with poorer performance in 2 dB compared to 7 dB SNR. As anticipated based on previously published data, there was no effect of either the strength of noise reduction or noise reduction *per se* on speech recognition (see Table 3).

Table 3: Speech recognition

	b	SE	p
SNR	1.41	0.05	<0.001***
NR (on vs off)	0.03	0.07	0.6
NR (mild vs strong)	-0.04	0.06	0.5

Table 3: Main effects of SNR and noise reduction on speech recognition, with significant effects highlighted in bold font (*** significant at $\alpha = 0.001$).

Visual monitoring (in isolation)

To examine whether there were any learning or fatigue effects on the secondary task performance, reaction time and accuracy data were compared across the three visual monitoring test blocks in isolation (i.e. not in combination with the speech recognition task). One visual monitoring block was completed at the start of the test session and two blocks at the end of the test session.

A linear mixed effects models (using the *lme()* function from the *nlme* package in R) was used to analyse the reaction time data, and a logistic mixed effects model was used to analyse the accuracy data (binary dependent variable indicating correct or incorrect identification of repeated image). Both models included block (categorical variable: 1, 2, or 3) as a fixed factor and participant as a random factor. Models with session as an additional fixed factor did not provide a better fit for the data. One contrast was set up to examine the effect of test block (1 vs. 2 and 3).

The results showed no significant effects of test block for either the accuracy or the reaction time data (accuracy: $b = 0.4$, $SE = 0.3$, $p = 0.1$; reaction time: $b = 0.006$, $SE = 0.01$, $p = 0.6$), suggesting that participants did not show any learning or fatigue effects over the course of the test session (see Fig. 5).

Figure 5: Reaction time and accuracy scores for the visual monitoring task performed in isolation across three test blocks. Block 1 was performed at the start of the session, while blocks 2 and 3 were completed at the end of the test session. Any differences on this task across test block might indicate potential fatigue or learning effects.

Multitasking

Figures 6 and 7 illustrate the two multitasking measures, normalized reaction time and normalized accuracy, for the three different noise reduction settings (off, mild, strong) in two different SNRs (2 and 7 dB). Note that while the normalized reaction time data showed poor test-retest reliability, these data are nonetheless discussed here for the sake of completeness.

Figure 6: Normalized reaction time, a measure of listening effort, under different noise reductions settings (off, mild, strong) for two different SNRs (2 and 7 dB). The higher the normalized scores are, the more listening effort was expended by the listener. Note that negative scores suggest that participants perhaps did not maintain speech recognition as their primary task.

Figure 7: Normalized accuracy score, a measure of listening effort, for different noise reduction settings of the hearing aids (off, mild, strong) with the sentences presented in babble at two SNRs (2 and 7 dB). The higher the normalized scores are, the more listening effort was expended by the listener. Note that negative scores suggest that participants perhaps did not maintain speech recognition as their primary task.

Linear mixed effects models with SNR (categorical variable: 2 and 7 dB SNR) and noise reduction (categorical variable: off, mild, strong) as fixed factors and participant as a random factor were used to analyse the measures of multitasking. Model comparisons indicated that including session in the models did not improve the model fit. Similarly, adding an interaction term (SNR x NR) did not result in a better fitting model (reaction time: likelihood ratio = 2.6, $p = 0.3$; accuracy: likelihood ratio = 1.7, $p = 0.4$). Two contrasts were again set up to examine the effects of noise reduction (off vs. mild and strong; mild vs. strong).

The results showed no effects of either noise reduction setting or SNR on the normalized accuracy or reaction time scores (all $p > 0.1$; see Table 4 and 5). Note also that a few normalized reaction times and accuracy scores were negative, suggesting that occasionally participants perhaps did not maintain speech recognition as their primary task. This issue will be further considered in the discussion.

Table 4: Normalized reaction time (dual-task)

	b	SE	p
SNR	-0.4	1.7	0.8
NR (on vs off)	3.0	1.2	0.2
NR (mild vs strong)	1.1	0.5	0.6

Table 4: Main effects of SNR and noise reduction on normalized reaction times.

Table 5: Normalized accuracy (dual-task)

	b	SE	p
SNR	-0.01	0.03	0.6
NR (on vs off)	0.04	0.05	0.4
NR (mild vs strong)	<0.01	0.04	>0.9

Table 5: Main effects of SNR and noise reduction on normalized accuracy scores.

Discussion

Does digital noise reduction improve the ability to multitask in adults fit with hearing aids?

The benefits of digital noise reduction have been clearly established when normal-hearing individuals are presented with simulated NR (e.g., Sarampalis et al., 2009; Neher, Grimm, & Hohmann, 2014). In the present study, we found no overriding effect either of the presence of NR or adjustment of its strength in typical older hearing-impaired listeners fit with wearable hearing aids. This is consistent with the findings of Desjardins (2016), who found that strong NR failed to improve performance on a dual-task in adult cohorts with similar age and hearing loss characteristics to those in the present study.

Conversely, Desjardins and Doherty (2014) found reduced listening effort in a group of 12 hearing-impaired adults fit with strong NR. The discrepancy may lie in the listening environment. Desjardins and Doherty noted poorer performance on a dual-task paradigm at a speech-in-noise threshold of 50% correct--that is, under relatively unfavourable listening conditions--but did not demonstrate poorer dual-task performance at more favourable SNRs. This suggests that the benefits of NR on listening effort may be more likely to occur in highly unfavourable conditions (i.e. more unfavourable than the conditions used in the present study).

In typical everyday environments, with SNRs likely to be 5 dB or higher (Smeds, Wolters, & Rung, 2015), conditions therefore are not necessarily such that NR is likely to affect the ability to perform multiple tasks simultaneously. Noise levels similar to the study conditions where improved dual-task performance was demonstrated are more likely in restaurants, loud transportation such as aircraft or trains (Olsen, 1998), and classrooms. Of course, even if they occur a minority of the time, those noisy environments are arguably the most important environments in which to reduce listening effort and improve an individual's ability to perform multiple tasks simultaneously (e.g. taking notes while listening to the

teacher). Nonetheless, discussions with prospective NR users--particularly those where NR will add to the cost of a hearing aid--should include realistic expectations for the benefits of NR for each individual's lifestyle. Conversely, prospective NR users whose habitual social or work environments consist of unfavourable SNRs are likely to receive greater overall benefit from NR.

The balance between removing noise and altering speech

Previous studies of hearing aids employed strong noise reduction, which potentially could have resulted in speech distortion that offset noise reduction benefits (Arehart, Souza, Kates, Lunner, & Pedersen, 2015; Brons et al., 2012). To understand those distortions, consider how NR works. A typical approach is spectral subtraction, where noise is estimated during non-speech intervals (Boll, 1979). The estimated noise spectrum is then digitally removed from the speech plus noise signal, hopefully retaining only speech. The imperfect nature of estimating a dynamic noise results in partial retention of the noise components, and/or inadvertent removal of speech components. Should considerable speech alteration occur, increased listening effort might be required to parse an unfamiliar signal, thus likely affecting the cognitive resources available to perform a competing task. Simulation studies suggest such an effect can occur, resulting in lower speech recognition (Arehart, Souza, Baca, & Kates, 2013) and increased listening effort (Neher, Grimm, Hohmann, & Kollmeier, 2013). A recent study by Huber et al. (2017) showed that people, at least those with normal hearing, tend to rate speech both as more distorted and more effortful to understand under strong compared to mild noise reduction settings. Those simulations created more extreme processing than would commonly occur in commercial hearing aids. However, it is probable that in speech-in-noise environments processed by hearing aids implemented with NR, listeners must navigate two effects: the masking effects of the noise (slightly improved by NR); and the degradation of the

target speech by NR. While there is considerable information available as to the effects of noise masking in listeners with hearing loss, there are fewer data regarding their susceptibility to speech degradation of the type and magnitude that might be created by NR.

The present data suggest that, in commercially available hearing aids and in relatively favourable everyday listening scenarios, the effects of mild NR may be similar to the effects of strong NR. That is, mild noise reduction (which, hypothetically, would have lower levels of speech distortion) also does not affect dual-task performance, at least in the implementation tested here. That finding raises another issue: it is difficult to make direct comparisons across studies without a universal quantification of noise reduction strength. To put this another way, “strong” for one manufacturer may be more similar in terms of change in dB to “mild” noise reduction from another manufacturer. The present study and a small number of other studies quantified the effect of NR in terms of change in SNR (Bentler et al., 2008; Gustafson et al., 2014). However, SNR may not be the most appropriate categorization, because it considers only changes to noise level and discounts changes to speech acoustics and naturalness. Even fewer studies have quantified changes to the speech signal (Gustafson et al., 2014; Neher et al., 2014). Such quantification would facilitate understanding of the effects of NR, and of hearing aid processing in general, across commercial platforms.

Interpreting multitasking in the context of acoustic hearing aid effects

The present study employed a single manufacturer and model of hearing aid, mimicking the situation that would occur for a typical clinical fitting. An important issue is the extent to which results are generalizable to other hearing aid models and/or manufacturers. In the present study, acoustic recordings verify that NR is active and noise is reduced. Accordingly, the present implementation represents a likely clinical scenario, while acknowledging that products with substantially different NR may produce different outcomes.

Limitations of the dual-task paradigm used in this study

Finally, it is important to acknowledge the limitations of the dual-task paradigm used in this study. Test-retest data indicated that the normalized reaction time scores were not consistent across test sessions and therefore not deemed reliable. This is perhaps not so surprising, however, given that reaction times become less consistent as we get older (e.g., Hultsch, MacDonald, Dixon, 2002). It is quite possible that a different dual-task paradigm (e.g., Sarampalis, Kallluri, Edwards, & Hafter, 2009) could provide a more sensitive and reliable measure to assess the effectiveness of NR strength on the ability to multitask. Perhaps a task that can assess changes in performance (maybe indicative of changes in attention or fatigue) throughout the course of a particular block could pick up on more subtle differences between different NR settings. Test-retest reliability analyses showed that the intelligibility and normalized accuracy scores were consistent across test sessions. That analysis supports that the dual-task paradigm used in this study has validity and can be used to shed light on people's abilities to multitask in different listening conditions.

Another consequence of the dual-task paradigm used in this study is that it does not distinguish between responses related to three distinct processes: listening to the sentence; repeating the sentence; and waiting for the next sentence. It is possible that varying the strength of the noise reduction algorithm in the hearing aids has the greatest effect on performance on the secondary task while the participant is listening to the sentence (i.e. listening effort).

Summary and conclusions

While NR undoubtedly has a range of benefits that are noticeable to the wearer, both the acoustic analysis and the measures of multitasking presented here suggest that adjustment of NR parameters is likely to have more minimal effects than expected, at least in environments with a relatively favourable SNR. Therefore, adjustment of NR settings in the clinic is perhaps not worthwhile if the aim is to improve speech recognition or aid multitasking.

Declaration of Interest

The authors report no conflicts of interest.

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