Research Article

Preference for Combinations of Hearing Aid Signal Processing

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ABSTRACT

Purpose: The purpose of this study was to determine how *multiple* types of signal processing activated *together* influence listeners' preferences. **AQ1**
Method: Participants were adults with mild to moderately severe sensorineural hearing loss. Stimuli were spatialized low-context sentences mixed with six-talker babble at 3 and 8 dB signal-to-noise ratios (SNRs). Stimuli were processed with three common hearing aid processing algorithms: wide dynamic range compression (WDRC), frequency compression (FC), and digital noise reduction (DNR). A full-factorial design with two levels for each algorithm (WDRC & DNR: mild versus strong; FC: ON versus OFF; clinically relevant ranges) was evaluated. Preference was measured using a paired-comparison task within a choice-based conjoint analysis framework. Remote data collection methods were used. A signal fidelity metric quantified the acoustic effects across conditions.
Results: At 3 dB SNR, participants preferred a combination of Slow WDRC and Mild DNR, although the mean preference was small (odds ratio close to 1). At both SNRs when Strong DNR was used, Fast WDRC was preferred over Slow WDRC. This may be related to signal fidelity, which was lower for the combination of Fast WDRC and Mild DNR and higher for the combination of Slow WDRC and either Mild DNR or Strong DNR. There was no effect of FC on preference or signal fidelity.
Conclusions: WDRC and DNR together influenced both listeners' preferences and signal fidelity in the investigated listening conditions. On average, the small effect sizes suggest that minor fine-tuning adjustments to hearing aid algorithms may not result in a substantial change in clinical outcomes.

Hearing aids are equipped with various signal processing algorithms aimed at restoring or improving perceptual abilities for individuals with hearing impairment. Each algorithm is designed with a specific purpose. For example, wide dynamic range compression (WDRC) is designed to restore audibility for soft and average sounds while maintaining comfort for loud sounds (Dillon, 2012); digital noise reduction (DNR) is designed to reduce interfering noise from speech for improving listening comfort (Bentler & Chiou, 2006), whereas frequency-lowering

methods such as frequency compression (FC) are designed to restore the audibility of high-frequency sounds by moving these sounds into lower frequency regions that are less damaged by hearing loss (Alexander, 2016). Each of these signal processing algorithms is controlled by settings/parameters that modify the hearing aid output. For instance, WDRC speed is controlled by the attack time and release time settings. A fast-acting WDRC setting (attack times < 10 ms and release times < 250 ms) improves audibility of soft sounds (Davies-Venn et al., 2009; Souza & Turner, 1998, 1999) but introduces more temporal envelope distortions compared to a slow-acting WDRC setting (Alexander & Masterson, 2015; Jenstad & Souza, 2005; Moore, 2008). DNR is typically controlled by the intended strength of noise reduction in combination

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with the level of noise in the environment, that is, stronger noise reduction may be applied to loud and noisy environments, whereas weaker (milder) noise reduction may be necessary in relatively quieter environments (Bentler & Chiou, 2006; Bentler et al., 2008). While stronger DNR can successfully reduce the noisy portions of the speech and noise signal, this setting may result in the removal of important overlapping speech content compared to weaker DNR (Brons et al., 2013; Loizou & Kim, 2011). FC strength is controlled by the start frequency and compression ratio. Lower start frequencies and higher compression ratios provide more access to high-frequency sounds (Alexander et al., 2014) but can result in the disruption of important information-bearing low-frequency portions of the signal such as vowels and formant transitions (Alexander, 2016; McDermott, 2011; Souza et al., 2013).

The specific settings selected for any given signal processing algorithm may improve certain targeted speech cues while unintentionally disrupting others. Perceptual consequences of these processing settings for listeners with hearing impairment may partly depend on trade-offs among these speech cues. Studies to date have mostly examined the impact of individual signal processing algorithms on intelligibility and quality outcomes for listeners. For instance, it has been shown that at least certain listeners who are more susceptible to temporal envelope distortions, such as those with lower working memory and/or more severe hearing losses, have poorer speech intelligibility with fast-acting WDRC than with slow-acting WDRC (Davies-Venn & Souza, 2014; Davies-Venn et al., 2009; Souza, Arehart, Shen, et al., 2015; Souza & Sirow, 2014; Stone & Moore, 2007; Stone & Moore, 2008). Across studies, sound quality has been consistently rated as worse with fast-acting WDRC compared with slow-acting WDRC (Hansen, 2002; Neuman et al., 1998; Souza, Arehart, Shen, et al., 2015). However, there is evidence that listeners with certain characteristics (e.g., those with higher working memory and milder losses) do have better speech intelligibility with fast-acting WDRC compared with slow-acting WDRC (Lunner & Sundewall-Thorén, 2007; Souza, Arehart, & Neher, 2015; Souza, Arehart, Shen, et al., 2015). For DNR, there is evidence across studies that speech intelligibility is compromised as the amount of DNR increases, although improved listening comfort and reduced listening effort are also reported with stronger DNR settings (Bentler et al., 2008; Desjardins, 2016; Lowery & Plyler, 2013). The trade-off for FC is that stronger settings including a lower start frequency and higher compression ratio improve the intelligibility of high-frequency phonemes (such as /s/ and /sh/), but the same settings decrease intelligibility for vowels and other consonants (Alexander, 2016) and result in poorer sound quality (Salorio-Corbetto et al., 2017; Souza et al., 2013).

While objective methods such as real-ear verification are used to adjust individualized hearing aid gain for the patient (Valente et al., 2006) and validation methods such as subjective questionnaires exist to determine the effectiveness of the hearing aid (Ricketts et al., 2019), audiologists often also use informal measures of preference to make fine-tuning adjustments by asking the listener which setting they "prefer." A survey by Anderson et al. (2018) revealed that majority of audiologists (total respondents were 251) used patient reports to fine-tune features such as WDRC (98%), DNR (96%), and FC (80%). Some hearing aid manufacturers have recently introduced user-driven fine-tuning of hearing aid gain in real-world contexts based on the user's preferences and machine learning (e.g., Balling et al., 2021; Fabry et al., 2021). However, **AQ2** studies have not focused on how specific algorithm settings influence listeners' preferences, particularly when these algorithms are activated simultaneously in hearing aids. If the trade-offs resulting from processing settings can impact speech intelligibility and/or quality, they must certainly also influence the preference that listeners have for these algorithms.

In this study, the emphasis is on combinations of signal processing algorithms because such an approach is reflective of real-world hearing aid use and function. Moreover, there is evidence that one type of signal processing can modulate or compound the acoustic and perceptual effects of another type of signal processing when they are activated together. For example, the presence of DNR was shown to counteract the negative effect of WDRC on signal-to-noise ratio (SNR; i.e., increased background noise) when they were activated together in a hearing aid (Brons et al., 2015; Wu & Stangl, 2013). While the acoustic effects did not translate to changes in speech intelligibility, listeners reported lower annoyance levels (Brons et al., 2015) and higher acceptable noise levels (Wu & Stangl, 2013) for WDRC activated along with noise reduction. When signals were processed with FC and WDRC together, FC had an additive effect on the overall signal modifications (Alexander & Rallapalli, 2017; Souza, Arehart, Shen, et al., 2015); that is, the speech envelope was distorted due to FC over and above the distortions caused by WDRC. Speech intelligibility and quality of the processed signal were also affected more when FC and fast-acting WDRC were combined in comparison to slow-acting WDRC alone (Souza et al., 2019) or FC combined with slow-acting WDRC (Souza, Arehart, Shen, et al., 2015). With evidence that combinations of two types of signal processing algorithms affect acoustic and perceptual outcomes (i.e., speech intelligibility and quality), it is highly likely that such combinations of signal processing algorithms will also influence listeners' preferences. Furthermore, when speech intelligibility and sound quality outcomes from a hearing aid algorithm are

at odds (e.g., as a result of DNR), understanding the listener's preference may guide the audiologist during hearing aid fitting. Therefore, a systematic study is needed to understand listener's preferences for such combinations of hearing aid settings to appropriately guide clinical decisions.

Considering the arguments previously presented, the approach to determining preference for multiple signal processing algorithms will need to account for trade-offs presented by parameter choices for each signal processing algorithm and the relationship between such choices across algorithms. To that end, this study adapts a method known as choice-based conjoint analysis to capture the trade-offs inherent in signal processing parameters in hearing aids and to determine the relative importance across different algorithms. Choice-based conjoint analysis has been used extensively in market research and to elicit preferences related to health care delivery (Ryan & Farrar, 2000). According to Ryan and Farrar, it is a rigorous method based on the premise that any product can be characterized by certain attributes. The degree to which an individual prefers this product depends on the levels of these attributes.

Few researchers have used the conjoint analysis method to determine preference for physical and functional hearing aid attributes (Bridges et al., 2012; Meister et al., 2001). For example, Meister et al. (2001) studied the relative importance of 12 hearing aid attributes ranging from speech perception in quiet and noise, handling, sound quality, localization, and feedback in a group of 93 experienced hearing aid users. Using the conjoint analysis method, they found that speech perception was the most important attribute, whereas sound quality was the most significant indicator of satisfaction. Similarly, Bridges et al. (2012) studied the relative importance of seven hearing aid attributes including quiet and noisy environments, comfort, feedback, battery life, water/sweat, and purchase cost. Using the conjoint analysis method, they found that hearing aid users were willing to pay a higher price for a hearing aid that is more effective in noisy environments. That is, the users were willing to trade cost for better noise management in hearing aids. While Meister et al. and Bridges et al. focused on the hearing aid as a commercial product, they did not address preference for specific settings of hearing aid signal processing algorithms that ultimately influence speech intelligibility in noise and sound quality outcomes.

AQ3 **Purpose of This Study**

The purpose of this study was to determine listeners' preferences when a combination of hearing aid signal processing algorithms was activated to different levels. Adaptation of the conjoint analysis approach is well suited for the proposed project because it emulates the hearing aid experience in the real world, where multiple signal processing algorithms activated together result in the overall output. These signal processing combinations included two levels each of WDRC, DNR, and FC. Preference was elicited at two different SNRs (i.e., background noise levels). It was hypothesized that listeners' preference for a certain level of signal processing would depend on two factors. First, preference will depend on the levels of other signal processing algorithms present in the hearing aid. Each type of signal processing algorithm will influence preference for the remaining signal processing algorithms to different extents. Second, preferences for each signal processing algorithm and the relationships among them will depend on the SNR. This study used remote data collection methods to maintain safety standards during the COVID-19 pandemic. To quantify the combined acoustic effects of hearing aid signal processing and background noise, this study measured envelope fidelity using a cepstral correlation metric (Kates & Arehart, 2014).

Method

Participants

Thirty-seven adults (22 men) in the age range of 54–93 years ($M = 75.7$, $SD = 8.5$) with bilateral mild to moderately severe sensorineural hearing loss were recruited for the study. One participant could not complete the study due to personal reasons, resulting in a total of 36 adults who participated in the study. Based on an a priori power analysis, the minimum sample size required was calculated corresponding to the following formula: $n \geq \frac{c.500}{t.a}$, where n **AQ4** is the total sample size, c is the number of analysis cells (equal to the largest product of levels of any two algorithms), t is the number of choice tasks, and a is the number of alternatives. In the full factorial design in this study, there are 56 choice tasks, one alternative for each choice, and a product of levels from any two algorithms equal to 4. This resulted in a minimum sample size of 36.

Twenty-one participants were hearing aid users with at least 1 year of experience at the time of study recruitment. Air-conduction thresholds were obtained at octave and midoctave frequencies between 250 and 8000 Hz. Bone-conduction thresholds were obtained at octave frequencies between 500 Hz and 4000 Hz. All participants had symmetric audiograms for both ears (asymmetry was defined as a difference of at least 15 dB HL at two or more frequencies or a difference of at least 20 dB HL at one frequency between 250 and 3000 Hz). All participants had air–bone gaps of less than 15 dB at all test frequencies.

Participants had an audiogram completed in a double-walled sound-treated booth by an audiologist,

within 24 months of recruitment for the study. To maintain socially distanced testing during the COVID-19 pandemic, anyone with an audiogram over 12 months was retested with a validated automated audiometer in a quiet room in the laboratory and confirmed to have stable hearing within ±10 dB across test frequencies. The equipment used for this purpose was the Grason-Stadler Automated Method for Testing Auditory Sensitivity FLEX (GSI AMTAS FLEX; Margolis et al., 2010, 2016; Margolis & Moore, 2011). The exception were five participants who were unable to provide a previous audiogram and completed their first hearing test using the automated audiometer in a quiet room in the laboratory. For these participants, bone-conduction thresholds could not be obtained. However, none of these participants reported any history of outer- or middle-ear disorders. Figure 1 shows the air-conduction thresholds of all 36 participants. The average four-frequency pure-tone average (PTA; 500, 1000, 2000, and 4000 Hz) was 41.5 dB (SD = 10.9) for the right ear and 40.5 dB (SD = 11.4) for the left ear. Participant age exhibited a statistically significant correlation with the average four-frequency PTA for both ears such that older adults also had a greater degree of hearing loss (r = .418, p = .011). Participants were native English speakers, reported no otologic or neurologic disorders, were in general good health based on self-report, and had normal cognitive functioning based on the Montreal Cognitive Assessment (MoCA) completed either in person or over video, within 12 months of recruitment for the study (Nasreddine et al.,

2005). The criterion for passing the MoCA was a score greater than 22 (Luis et al., 2009; Rossetti et al., 2011). Normal cognitive function for one participant was determined based on the telephone version of the MoCA as he did not have access to a computer for video. The criterion for passing the telephone version of the MoCA was a score greater than 19 (Katz et al., 2021). Additionally, three participants could not complete the MoCA due to their personal time constraints; however, these participants did not report any significant history of cognitive issues. All participants completed an informed consent process approved by Northwestern University's institutional review board.

Stimuli

Stimuli were sentences from the Institute of Electrical and Electronics Engineers database (Rothauser et al., 1969), spoken by two male and two female talkers (Panfili et al., 2017). Background noise consisted of six-talker babble spoken by a different set of three male and three female talkers from the same database. To generate the babble, three sentences per talker were randomly selected. The sentences were concatenated without gaps and then cut to the same length as the target sentence plus 1-s lead and lag times. Onset and offset ramps of 250 ms each were applied to the six-talker babble. These steps were followed to generate babble for each trial.

A room simulator (Zahorik, 2009) was used to spatialize the speech and babble in order to approximate a

Figure 1. Air-conduction thresholds for the right and left ears of each participant (dashed lines). Solid lines show the average for all participants.
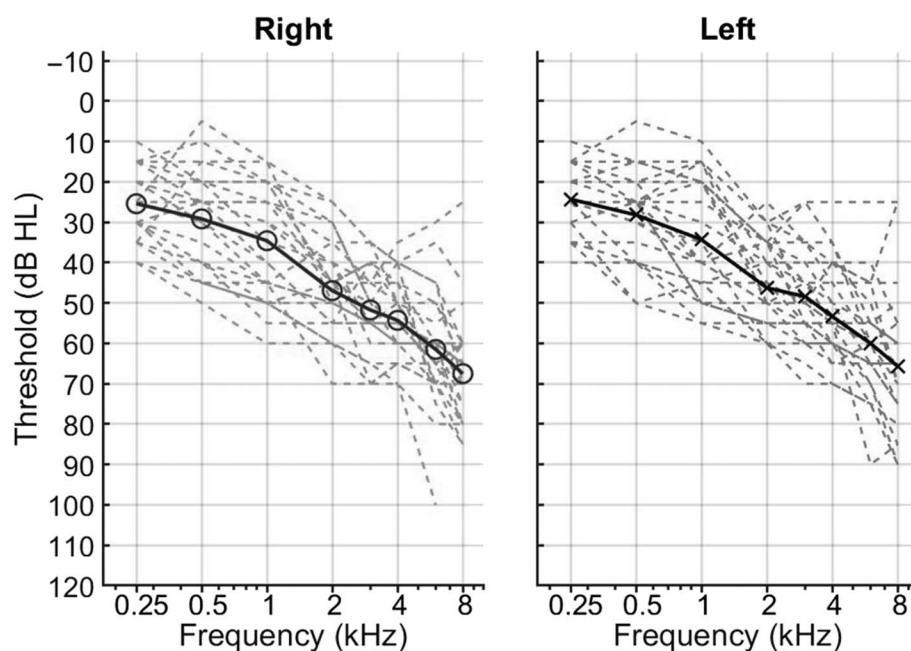
realistic listening situation under headphones. The simulated binaural room impulse responses (BRIRs) were generated for a small room (dimensions: $5.67 \times 4.26 \times 2.58$ m^3) with the listener seated in the center, the target sentence at 0° azimuth, and the individual babble talkers equally distributed between 90° and 270° azimuths (see Figure 2). Individual talkers were randomly assigned to one of the six azimuths in each trial. Absorption coefficients represented a simulated anechoic chamber ($\alpha = 1.0$ at all frequencies). BRIRs were convolved with each sound source (individual talker) and then mixed at a given SNR to generate the speech-in-noise signals. SNRs were 3 dB (low) or 8 dB (high), representing the lower and upper boundaries of real-world SNRs (Smeds et al., 2015; Wu et al., 2018). The level of the sentence was fixed at 65 dB SPL, and the overall level of the six-talker babble was adjusted according to the SNR. All signal processing and experimentation were carried out using MATLAB (MathWorks).

Hearing Aid Processing

The spatialized stimuli were processed through a hearing aid simulator (Arehart et al., 2021; Kates et al., 2019), which provided individualized gain across frequencies for each participant, based on the NAL-NL2 prescriptive method (Keidser et al., 2012). Because participants had symmetric hearing, the individualized gain for both

Figure 2. Simulated room configuration ($5.67 \times 4.26 \times 2.58$ m^3) with listener (L) seated in the center and the speaker (S; target sentence) directly in front at 0° azimuth. Noise sources are individual talkers (B1–B6; 3 men & 3 women) equally spaced between 90° and 270° around the listener. All sources of speech and babble are at a 1-m distance from the listener.
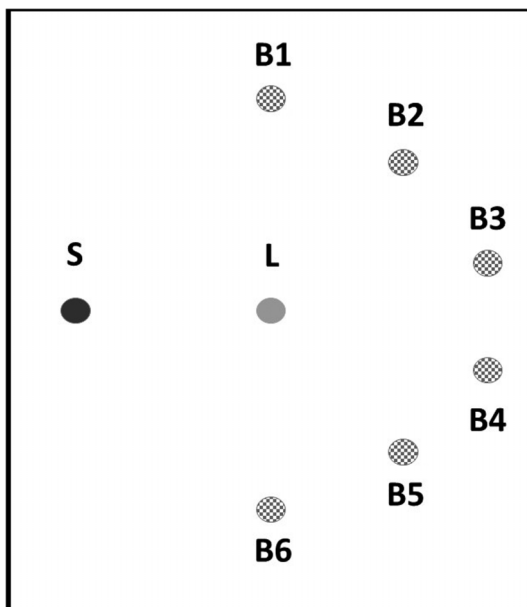
ears was based on relatively better ear thresholds between 250 and 3000 Hz. The hearing aid processing was a linear-phase 12-channel filter bank with center frequencies at 125, 250, 315, 500, 750, 1000, 1500, 2000, 3000, 4000, 5000, and 6000 Hz. The input signal was filtered through a microphone response for a behind-the-ear hearing aid shell and a fully occluded vent (Arehart et al., 2021; Kates et al., 2019). Within each hearing aid channel, the noisy signal was first subjected to FC, followed by DNR, and then WDRC. The hearing aid processing settings were based on a realistic range of settings available in commercial hearing aids (Rallapalli et al., 2018).

WDRC speed was varied between fast-acting (Fast) and slow-acting (Slow) with release times of 50 and 2000 ms, respectively. The attack time was always 5 ms. FC was based on sinusoidal modeling (Souza et al., 2013) and was either OFF or ON. When FC was ON, the start frequency and compression ratio were determined by the degree of hearing loss and audiometric configuration (Arehart et al., 2021). Across participants, the start frequency ranged between 4.5 and 4.6 kHz and the compression ratio ranged between 2.7 and 2.8. Only one participant received a relatively lower start frequency at 2.9 kHz and a compression ratio of 2.1 due to a greater slope of high-frequency hearing loss. DNR was implemented using a method commonly used in hearing aids known as Wiener filtering (Dillon, 2012; Kates, 2017; Ricketts et al., 2019), and maximum attenuation per channel was either mild at 3 dB or strong at 12 dB.

Preference

An adaptation of the choice-based conjoint analysis approach was used to elicit preferences (Bridges et al., 2012). Conjoint analysis typically involves identifying attributes, assigning levels, formulating scenarios, establishing preferences, and data analysis. Instead of using a qualitative analysis to select attributes, this study used predetermined hearing aid algorithms commonly available in devices and ecologically valid SNRs (Smeds et al., 2015; Wu et al., 2018). Therefore, attributes were defined as the signal processing algorithms (WDRC, DNR, and FC) presented to the listener. An additional attribute was the SNR. Each algorithm was assigned two levels: mild (or off) and strong. Figure 3 shows the signal processing algorithm and the levels within each algorithm. For each algorithm, the mild levels are shown in light gray boxes, and the strong levels are shown in dark gray boxes.

The general experimental design of conjoint analysis was retained (see Figure 3), but preference was elicited for auditory stimuli, rather than with a questionnaire. A set of attributes (i.e., some combination of the three signal processing algorithms) together represented a "Hearing Aid." A full factorial design of all the signal processing

Figure 3. Schematic of the experimental design. Signal processing algorithms are WDRC, FC, and DNR. Light and dark gray boxes indicate the mild and strong level settings for each algorithm. Attn = attenuation; DNR = digital noise reduction; FC = frequency compression; HL = hearing loss; RT = release time; Sig. Proc. = signal process; SNR = signal-to-noise ratio; WDRC = wide dynamic range compression.
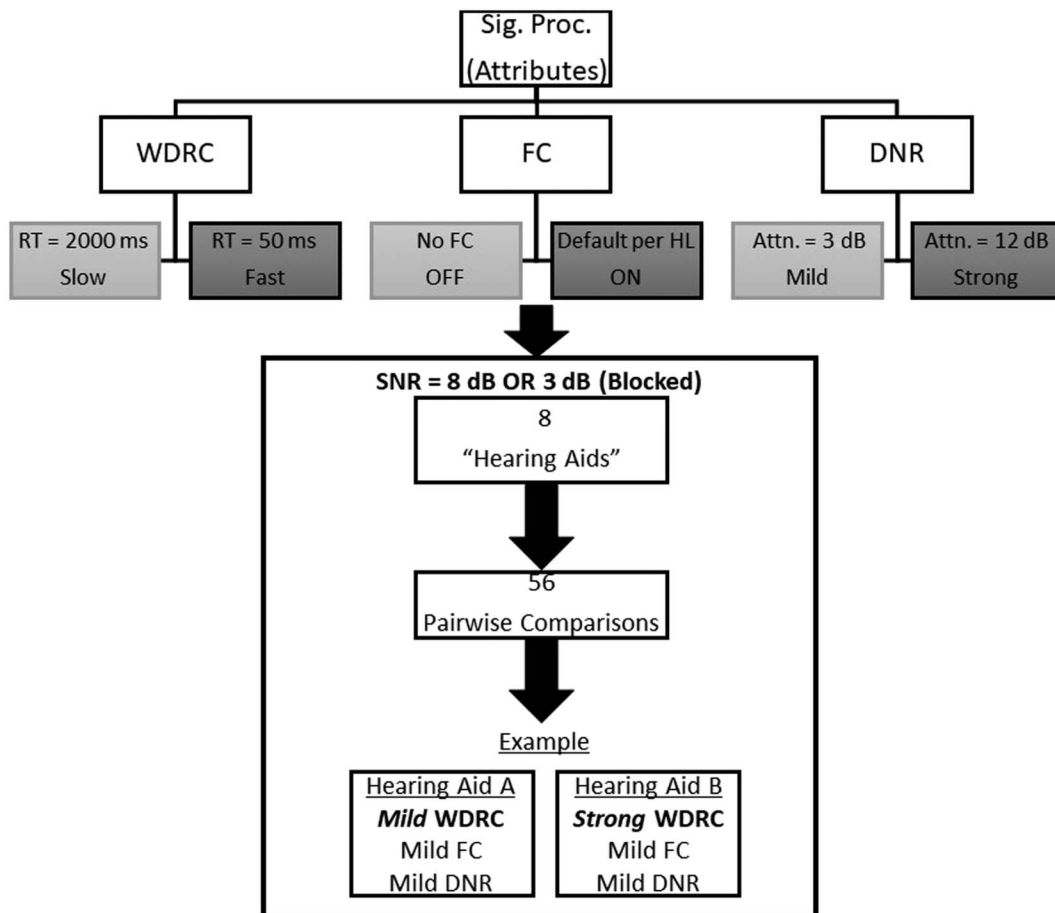
algorithms resulted in eight possible "Hearing Aids": S1-Slow WDRC, Mild DNR, and FC OFF; S2-Slow WDRC, Mild DNR, and FC ON; S3-Slow WDRC, Strong DNR, and FC OFF; S4-Slow WDRC, Strong DNR, and FC ON; S5-Fast WDRC, Mild DNR, and FC OFF; S6-Fast WDRC, Mild DNR, and FC ON; S7-Fast WDRC, Strong DNR, and FC OFF; and S8-Fast WDRC, Strong DNR, and FC ON. SNR was the blocking variable. For each SNR level, this design generated 28 distinct and 4 identical comparisons between two "Hearing Aids." Each participant registered preferences for all 64 pairs. However, the final analysis involved 56 total "Hearing Aid" pairs (28 distinct comparisons per SNR × 2 SNR levels).

Procedure

Due to the COVID-19 pandemic, data collection was completed remotely. Feasibility of remote data collection for this experiment was established in a pilot study with nine participants who also completed a laboratory version of this study as it was originally designed prior to the pandemic (Rallapalli & Souza, in press). Participants were provided with a Surface Go 2 tablet (Intel Pentium CPU 4425Y, 1.7-GHz, 4-GB RAM, 64-bit) and calibrated Sennheiser HD25 headphones. The participant ran the experiment by controlling the presentation of pre-processed stimuli and entering responses on a custom executable MATLAB graphical user interface.

Two headphone screeners were included as part of the executable. Participants had to repeat each screener until they reached the passing criteria to proceed to the main experiment. The first screener was to make sure that participants used headphones instead of the tablet speakers (Woods et al., 2017). Three 1-s-long tones were presented with an interstimulus interval of 0.5 s. The frequency of the tones was 200 Hz. The presentation level of two tones was 70 dB SPL, and the third tone was 64 dB SPL. One of the two louder tones was presented 180° out of phase across the two headphones. The participant completed a

three-alternate-forced-choice task to identify the softest tone. If the participant was listening through the tablet speakers, instead of headphones, the tone that was 180° out of phase would be attenuated and the participant would not be able to correctly identify the softest tone. Participants were required to identify 5/6 trials correctly to pass this screener. If they failed the screener, they were instructed to check the headphone connection and repeat the screener.

The second screener was to verify that the right and left headphones were placed on the respective ears (Ellis & Souza, 2020). A 1-s-long tone burst was played at 70 dB SPL to either the right or the left ear randomly. The participant's task was to identify the ear in which the tone was played. Participants were required to identify 6/6 trials correctly to pass the screener. If they failed the screener, they were instructed to check the headphone placement and connection and repeat the screener.

For the main experiment, pairs of processed stimuli ("Hearing Aids") were presented through the headphones. During the task, participants were instructed to imagine a noisy listening situation in a restaurant, in which their intent was to communicate with the speaker directly in front of them. Participants recorded their responses on the tablet touchscreen by selecting the preferred stimulus in the pair. Each participant completed two sessions, for a total of 256 trials (128 trials per session). Thus, each participant completed all pairwise comparisons 4 times. The order of comparisons was randomized between the sessions and across participants. The aforementioned experimental procedures for paired comparisons have been successfully used in previous studies to elicit preference for combinations of various hearing aid settings (Amlani & Schafer, 2009; Kuk, 1994; Neher, 2014). Note that no instruction was provided to the participant regarding the speech intelligibility or quality of the signal as this study was focused on eliciting overall preference for the signal processing.

The following additional procedures were followed for remote testing. Based on the participant's choice, equipment was delivered either by shipping, socially distanced dropoff/pickup at the participant's residence or the campus curbside. Strict infection control protocols were followed throughout the process. The participant was provided with detailed written instructions with pictures to operate the tablet. Additional instructions were provided remotely over the phone or video as needed. De-identified data were stored in a hidden folder on the tablet and retrieved onto a secure laboratory drive immediately after the tablet was returned. A previous participant's data and stimuli were erased before providing the tablet for a new participant.

Signal Fidelity

Because it is expected that preference may be higher for the combination of hearing aid processing algorithms that preserve signal fidelity (Arehart et al., 2015, 2021; Souza et al., 2013; Souza et al., 2015), signal modifica- **AQ5** tions to the speech signal caused by the hearing aid signal processing and background noise were quantified using an acoustic metric known as cepstral correlation (Kates & Arehart, 2014). This metric incorporates a model of the impaired peripheral auditory system including frequency-specific threshold shifts and broadened auditory filters (Kates, 2013). The output of the model is the speech envelope (i.e., slowly varying fluctuations < 50 Hz) across 32 auditory frequency bands ranging from 80 to 8000 Hz. The envelope output for an unprocessed reference signal in quiet is compared to the envelope output for a processed signal in short time segments using cross-correlation. This provides the cepstral correlation value that accounts for changes in envelope fidelity across frequencies over time. Note that both the reference and processed signals are subjected to the effects of a listener's impaired auditory system. The cepstral correlation values range from 0 to 1, with 0 indicating complete deviation (least signal fidelity) to 1 indicating no deviation of the envelope of the processed signal (maximum signal fidelity) from the reference signal. Cepstral correlation was computed for the exact signal presented to each listener in the right ear across conditions. It should be noted that the cepstral correlation metric only accounts for monaural signal fidelity. Although the listeners in this study were presented binaural stimuli, cepstral correlation is being computed to determine the signal fidelity changes due to hearing aid processing, which were identical in both ears for a given participant.

Statistical Analyses

Preference

Statistical analyses were completed with a mixed-effects Bradley–Terry models with logit link function (ME-BT; Littell & Boyett, 1977) using the GLIMMIX procedure in SAS 9.4.

The first analysis considered the effect of a combination of levels and algorithms that constituted a "Hearing Aid," on preference. The dependent variable was a binary indicator of whether a particular "Hearing Aid" was preferred over other "Hearing Aids" using the choice-based conjoint analysis framework for paired comparisons. Fixed effects included each of the eight "Hearing Aids" (S1–S8) and random subject effects were included to account for correlation within subjects over repeated tasks. The reference "Hearing Aid" condition was S8 or the combination of Fast WDRC, Strong DNR, and FC ON (i.e., the stronger level settings for each hearing aid signal processing algorithm). Models were assessed separately at 3 and 8 dB SNR to evaluate preferences at both levels of background noise.

The second analysis considered the effects of individual hearing aid algorithms on preference using an ME-BT factorial model. The dependent variable was a binary indicator of whether a particular algorithm-level combination was preferred over another algorithm-level combination. Fixed effects included each algorithm (WDRC, DNR, and FC) and their two- and three-way interactions. Random effects for subjects were included to account for correlation within subjects over repeated tasks. Again, models were assessed separately at each SNR.

Signal Fidelity

A linear mixed-effects (LME) model was constructed using the MIXED procedure in SAS 9.4 to determine the effect of hearing aid signal processing algorithm on acoustic signal fidelity. Fixed effects included the algorithm (WDRC, DNR, and FC), SNR, as well as their two-, three-, and four-way interactions. The four-frequency PTA (from the ear used to compute frequency-specific gain) was also included in the model to account for signal fidelity changes due to the degree of hearing loss. Random effects

Figure 4. Boxplots showing observed proportion of preference (*y*-axis) across "Hearing Aids" (*x*-axis, S1–S8). Each panel shows a different SNR: Panel (a) = 3 dB SNR; panel (b) = 8 dB SNR. Labels on the *x*-axis show the hearing aid signal processing algorithms and levels constituting each "Hearing Aid." DNR = digital noise reduction; FC = frequency compression; SNR = signal-to-noise ratio; WDRC = wide dynamic range compression.
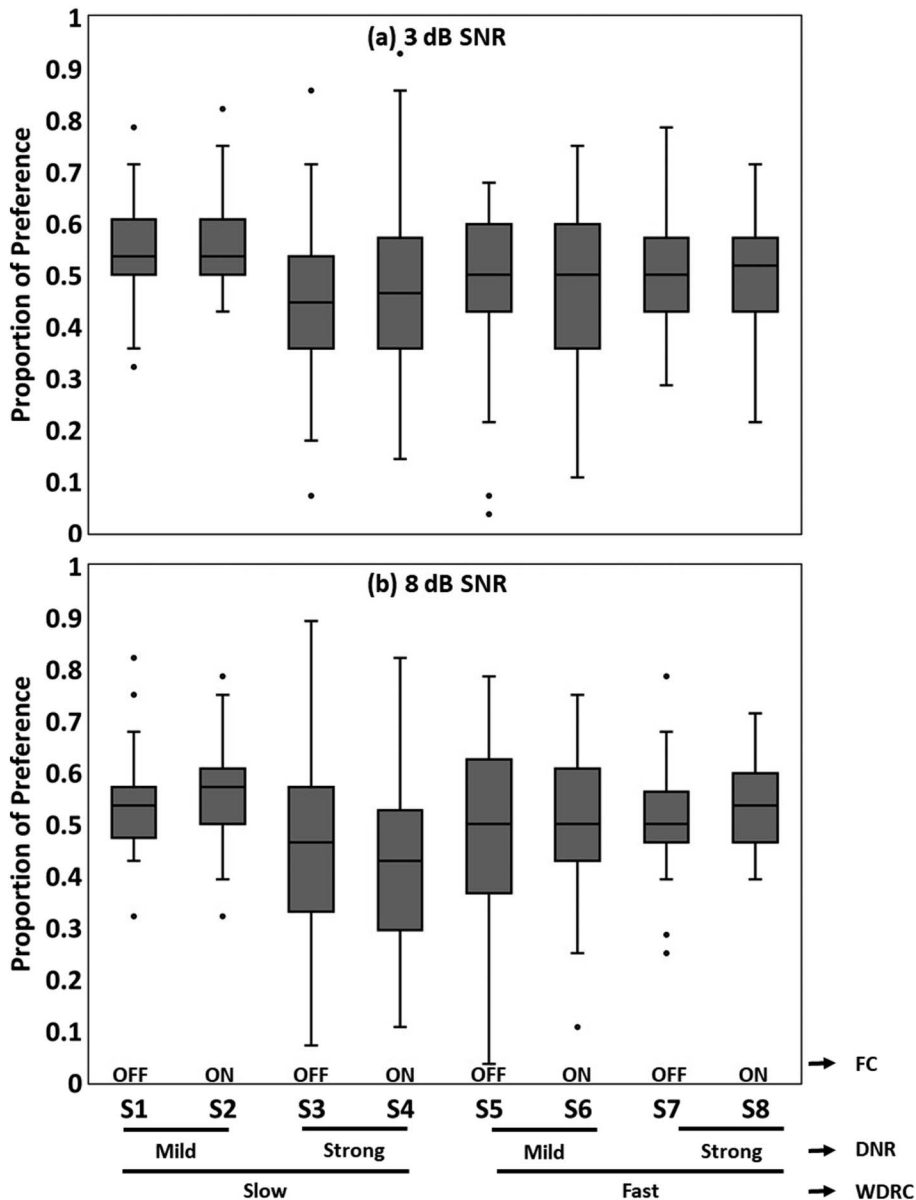
Table 1. Output from the mixed-effects Bradley–Terry logistic regression model with a binary outcome measure indicating whether a "Hearing Aid" was preferred or not (reference = S8 or Fast WDRC, Strong DNR, and FC ON).

SNR	"Hearing Aid"	b	b 95% CI		Odds ratio b	Odds ratio 95% CI		p
			LL	UL		LL	UL	
3 dB	S1	0.168	−0.025	0.361	1.183	0.976	1.435	.090
	S2	0.244	0.058	0.430	1.276	1.059	1.537	**.010**
	S3	−0.181	−0.361	−0.001	0.834	0.697	0.999	**.048**
	S4	−0.074	−0.249	0.099	0.928	0.78	1.105	.402
	S5	−0.066	−0.236	0.104	0.936	0.79	1.109	.444
	S6	−0.111	−0.278	0.056	0.895	0.757	1.058	.193
	S7	−0.008	−0.173	0.157	0.992	0.841	1.17	.924
8 dB	S1	0.020	−0.162	0.202	1.02	0.851	1.224	.829
	S2	0.062	−0.115	0.240	1.064	0.891	1.271	.491
	S3	−0.235	−0.409	−0.061	0.791	0.665	0.941	**.008**
	S4	−0.309	−0.479	−0.138	0.734	0.619	0.871	**< .001**
	S5	−0.172	−0.339	−0.004	0.842	0.712	0.996	**.045**
	S6	−0.154	−0.320	0.012	0.857	0.726	1.012	.068
	S7	−0.084	−0.249	0.080	0.919	0.78	1.084	.316

Note. The odds ratio is the exponential of the coefficient *b*. Separate models were computed at each SNR. Significant *p* values are highlighted in bold. WDRC = wide dynamic range compression; DNR = digital noise reduction; FC = frequency compression; SNR = signal-to-noise ratio; CI = confidence interval; LL = lower limit; UL = upper limit.

for subjects were included to account for correlations in metric values across conditions for the same participant. Residual diagnostics confirmed model assumptions.

Results

Preference

The distribution of proportion of preference across "Hearing Aids" is shown in Figure 4. The ME-BT model

results from the first analysis are shown in Table 1. At 3 dB SNR, there was a significant difference in preference for S2 and S3 compared to S8. Specifically, the odds of preferring S2 (Slow WDRC, Mild DNR, and FC ON) over S8 was 1.276 ($p < .05$). The odds of preferring S3 (Slow WDRC, Strong DNR, and FC OFF) over S8 was relatively lower at 0.834 ($p < .05$). The remaining "Hearing Aids" (S1, S4–S7) did not show a significant difference in preference over S8 ($p > .05$). At 8 dB SNR, there was a significant difference in preference for S3, S4, and S5 compared to S8. Specifically, the odds of preferring S3 (Slow WDRC, Strong

Table 2. Output from the mixed-effects Bradley–Terry logistic regression model with a binary outcome measure indicating whether a level of a signal processing algorithm (WDRC, DNR, and FC) was preferred on average across comparisons with other configurations within the choice-based conjoint analysis framework.

SNR	Effect	b	b 95% CI		Odds ratio b	Odds ratio 95% CI		p
			LL	UL		LL	UL	
3 dB	WDRC	0.082	−0.058	0.223	1.086	0.944	1.249	.249
	DNR	0.010	−0.130	0.151	1.01	0.878	1.163	.885
	FC	0.100	−0.042	0.242	1.105	0.958	1.274	.169
	WDRC × DNR	0.255	0.108	0.402	1.291	1.114	1.494	**< .001**
	WDRC × FC	0.045	−0.094	0.184	1.046	0.91	1.202	.524
	DNR × FC	0.089	−0.050	0.228	1.093	0.952	1.257	.208
	WDRC × DNR × FC	0.046	−0.096	0.189	1.048	0.909	1.208	.522
8 dB	WDRC	−0.011	−0.151	0.129	0.989	0.86	1.138	.878
	DNR	−0.073	−0.213	0.067	0.93	0.808	1.069	.307
	FC	0.036	−0.105	0.177	1.037	0.9	1.194	.618
	WDRC × DNR	0.175	0.028	0.321	1.191	1.029	1.378	**.019**
	WDRC × FC	0.091	−0.047	0.229	1.095	0.954	1.257	.198
	DNR × FC	0.046	−0.092	0.184	1.047	0.912	1.202	.516
	WDRC × DNR × FC	0.100	−0.041	0.242	1.106	0.96	1.273	.163

Note. The odds ratio is the exponential of the coefficient *b*. Separate models were computed at each SNR. Significant *p* values are highlighted in bold. WDRC = wide dynamic range compression; DNR = digital noise reduction; FC = frequency compression; SNR = signal-to-noise ratio; CI = confidence interval; LL = lower limit; UL = upper limit.

Figure 5. Boxplots showing observed proportion of preference as a function of DNR (Mild, Strong) and WDRC (Slow, Fast) levels. Each panel represents a different SNR: Panel (a) = 3 dB SNR; panel (b) = 8 dB SNR. Preference is averaged across trials and FC levels. Coefficient b represents the estimated change in preference between WDRC levels (Fast to Slow) at a particular level of DNR. DNR = digital noise reduction; FC = frequency compression; SNR = signal-to-noise ratio; WDRC = wide dynamic range compression. *p < .05.
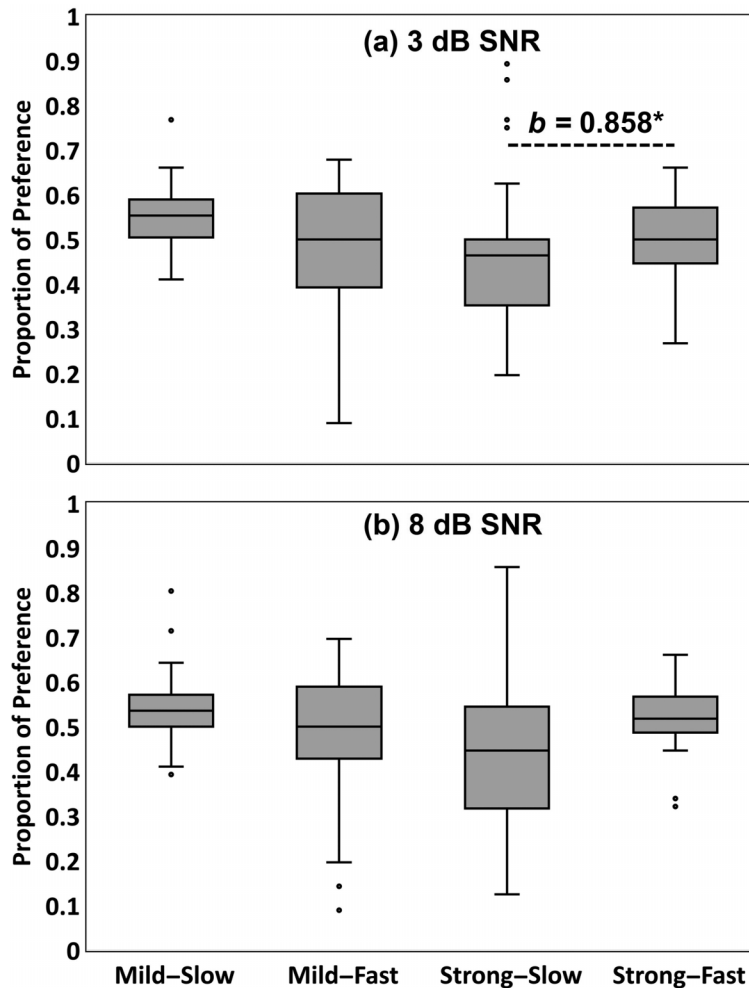
DNR, and FC OFF) over S8 was 0.791 (p < .01), whereas the odds of preferring S4 (Slow WDRC, Strong DNR, and FC ON) over S8 was slightly lower at 0.734 (p < .001). The odds of preferring S5 (Fast WDRC, Mild DNR, and FC OFF) over S8 was 0.842 (p < .05). The remaining "Hearing Aids" (S1, S2, S6, and S7) did not show a significant difference in preference over S8.

The ME-BT model results from the second analysis are shown in Table 2. At both SNRs, there was a significant interaction between WDRC and DNR. None of the remaining main effects and interactions were significant. Figure 5 shows the observed proportion of preference across the combination of DNR and WDRC levels. Post hoc analyses on the WDRC × DNR interaction were conducted by estimating the effect of WDRC at each level of DNR. A Bonferroni correction was applied to account for multiple comparisons. At 3 dB SNR, the odds ratio of

preferring a setting with Fast WDRC over Slow WDRC in the presence of Strong DNR was 2.360 (b = 0.858, p = .045). However, there was no significant difference between Fast and Slow WDRC in the presence of Mild DNR (b = −0.348, p = .110). At 8 dB SNR, there was no significant difference in preference between Fast and Slow WDRC in the presence of Strong (b = 0.710, p = .114) or Mild DNR (b = −0.391, p = .062).

Signal Fidelity

LME model results for signal fidelity are shown in Table 3. The main effects of SNR, WDRC, and DNR were significant. In addition, the two- and three-way interactions between SNR, WDRC, and DNR were significant. Therefore, post hoc analyses were conducted on the three-way interaction to examine the effect of WDRC at

Table 3. LME model output for signal fidelity (cepstral correlation; 1 = maximum).

Effect	Num DF	Den DF	F	p
SNR	1	16E3	14449.5	**< .001**
WDRC	1	16E3	1443.85	**< .001**
WDRC × SNR	1	16E3	6.06	**.014**
DNR	1	16E3	1334.73	**< .001**
DNR × SNR	1	16E3	18.66	**< .001**
WDRC × DNR	1	16E3	503.9	**< .001**
WDRC × DNR × SNR	1	16E3	10.49	**.001**
FC	1	16E3	0.09	.763
FC × SNR	1	16E3	0.74	.391
WDRC × FC	1	16E3	2.73	.099
WDRC × FC × SNR	1	16E3	1.66	.197
FC × DNR	1	16E3	0.05	.824
FC × DNR × SNR	1	16E3	0.11	.742
WDRC × FC × DNR	1	16E3	2.01	.157
WDRC × FC × DNR × SNR	1	16E3	2.99	.084
PTA	1	16E3	39.32	**< .001**

Note. Fixed effects include SNR (ref = 8 dB), WDRC (ref = Fast), DNR (ref = Strong), FC (ref = FC ON), and four-frequency PTA. Significant *p* values are highlighted in bold. LME = linear mixed-effects; WDRC = wide dynamic range compression; DNR = digital noise reduction; FC = frequency compression; SNR = signal-to-noise ratio; pure-tone average = PTA.

each level of SNR and DNR. A Bonferroni correction was applied for multiple comparisons. Figure 6 shows the observed signal fidelity across WDRC and DNR levels at each SNR.

At 3 dB SNR, Fast WDRC resulted in lower signal fidelity compared to Slow WDRC in the presence of Mild DNR ($b = -0.052$, $p < .001$). This effect was reduced in the presence of Strong DNR ($b = -0.015$, $p < .001$). At 8 dB SNR, a similar small effect of WDRC was observed in the presence of Strong DNR ($b = -0.014$, $p < .001$). However, this effect was more pronounced in the presence of Mild DNR ($b = -0.063$, $p < .001$). That is, Fast WDRC resulted in much lower signal fidelity compared to Slow WDRC in the presence of Mild DNR compared to Strong DNR at 3 and 8 dB SNRs, but with slightly greater effect size at 8 dB SNR. The main effect of PTA was significant such that a unit change in PTA resulted in a change in signal fidelity by 0.003 ($p < .001$). The main effect and interactions with FC were not significant.

Discussion

Signal Fidelity

As expected, SNR, DNR, and WDRC had significant effects on signal fidelity. In general, Fast WDRC resulted in lower signal fidelity compared to Slow WDRC. This is expected because faster WDRC speeds are known

to distort the temporal envelope of the speech signal (Alexander & Masterson, 2015; Jenstad & Souza, 2005; Moore, 2008), and this effect has been shown across previous studies using the cepstral correlation metric (Kates et al., 2018; Souza, Arehart, Shen, et al., 2015; Souza et al., 2019), as well as other measures of envelope distortion (e.g., Alexander & Masterson, 2015; Jenstad & Souza, 2005). However, the magnitude of distortion with WDRC depended on the level of DNR and background noise together. Specifically, at the 8 dB SNR, fast-acting WDRC reduced signal fidelity more in the presence of Mild DNR compared to Strong DNR. In order words, the magnitude of distortion due to fast-acting WDRC was tempered with more attenuation from DNR. At a 3 dB SNR, a similar pattern was observed, albeit the effect was slightly reduced in the presence of mild DNR. This is likely because distortion from the background noise was more dominant than the distortion from WDRC (Kates et al., 2018).

The interaction between WDRC and DNR processing is consistent with previous studies and can be explained based on the opposite effects of the compressor and noise reduction algorithms on background noise. It has been shown that WDRC reduces the SNR at the output of the hearing aid for a speech signal mixed with noise, especially at positive SNRs (Alexander & Masterson, 2015; Naylor & Johannesson, 2009; Souza et al., 2006). The compressor responds to the signal that fluctuates the most, be it speech or noise, and provides gain to the relatively low-level noise present in the "dips" of speech, making the overall output noisier. This effect is greater for fast-acting WDRC because the compressor responds quickly to changes in the input level compared to slow-acting WDRC (Jenstad & Souza, 2005). However, when DNR is introduced in the processing pathway, it attenuates the noisy portions of the signal prior to compression (at least in the hearing aid simulator implemented in this study), thus counteracting the noisiness resulting from WDRC (Brons et al., 2015; Wu & Stangl, 2013). The stronger DNR setting in this study likely removed a larger portion of the noise, and thus, the overall distortion from fast-acting WDRC was reduced compared to fast-acting WDRC combined with a milder DNR setting.

Preference

The interpretation for preference is based on the combined findings from the two ME-BT models. Of the three signal processing algorithms, results showed that only DNR and WDRC had a significant effect on listeners' preferences. Specifically, at 3 dB SNR, preference for the combination of Slow WDRC and Mild DNR was greater than that for the combination of Fast WDRC and Strong DNR. The combination of milder WDRC and DNR settings (i.e., Slow WDRC and Mild DNR) may

Figure 6. Boxplots showing signal fidelity (cepstral correlation; 1 = maximum) as a function of DNR (Mild, Strong) and WDRC (Slow, Fast). SNR is represented in different panels: Panel (a) = 3 dB SNR; panel (b) = 8 dB SNR. Signal fidelity is averaged across trials and FC levels. Coefficients b represent the estimated change in signal fidelity between WDRC levels (Fast to Slow) at each level of DNR. DNR = digital noise reduction; FC = frequency compression; SNR = signal-to-noise ratio; WDRC = wide dynamic range compression. ***$p < .001$.
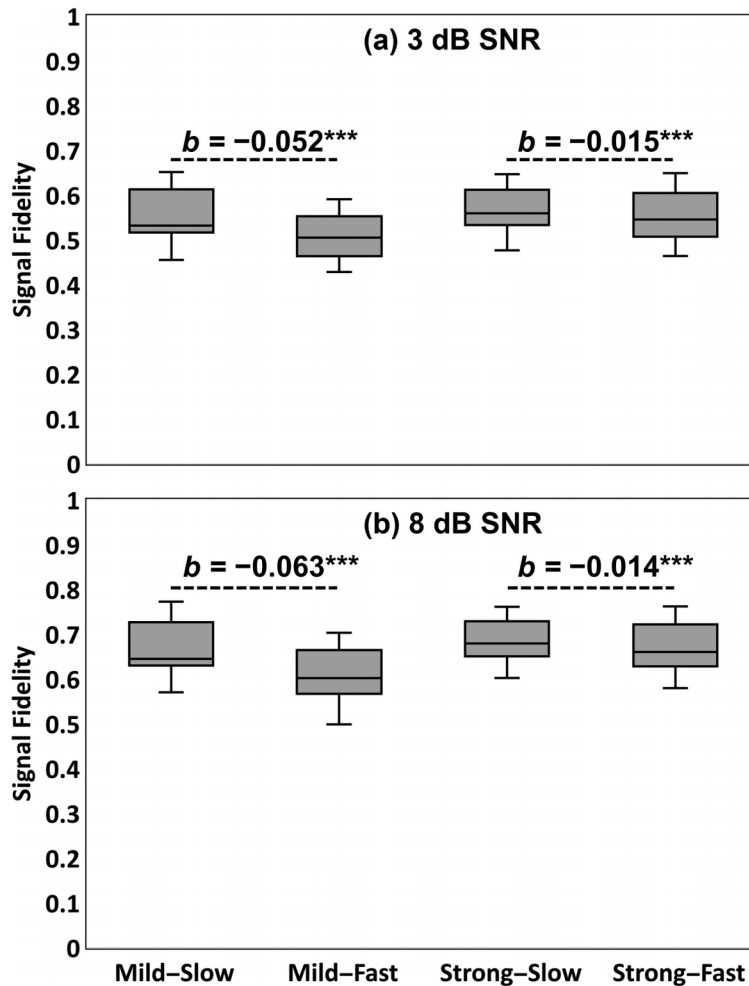
have collectively resulted in less signal distortion and less attenuation of the speech signal (required for maintaining intelligibility) and was thus preferred over Fast WDRC and Strong DNR (Bentler & Chiou, 2006). This is consistent with studies that measured preference separately with WDRC or DNR. Specifically, these studies showed that as the background noise levels increased, listeners preferred slower WDRC release times (Neuman et al., 1998) or less noise reduction strength (Neher et al., 2013).

On the other hand, preference for the combination of Fast WDRC and Strong DNR was greater than that for the combination of Slow WDRC and Strong DNR. Slow WDRC results in better signal fidelity but (presumed) poorer speech audibility when low-intensity phonemes are underamplified. In other words, at 3 dB SNR, Fast WDRC may have resulted in higher speech audibility compared to Slow WDRC in the presence of Strong

DNR, leading to a higher preference for the overall stronger WDRC and DNR combination. This effect is supported by studies focused on WDRC alone, showing that fast-acting WDRC improves performance over linear amplification (Souza & Turner, 1998, 1999) or slow-acting WDRC (Kowalewski et al., 2018) at low stimulus levels where audibility of speech sounds may be the driving factor.

At 8 dB SNR, listeners' preference for the combination of Fast WDRC and Strong DNR was greater than any combinations of Slow WDRC and Strong DNR. At 8 dB SNR, one might expect that the speech was relatively more intelligible than at 3 dB SNR. Speech audibility was likely no longer compromised by the hearing aid processing. In such a situation, the preference may have been influenced by better sound quality and listening comfort (e.g., Arehart et al., 2021). Studies that combined strong DNR with fast-acting WDRC have shown that stronger DNR settings

can reduce noisiness associated with fast WDRC and, in turn, reduce annoyance and make the signal more tolerable to the listener (Brons et al., 2014, 2015; Wu & Stangl, 2013). This is one potential explanation for why listeners may have preferred Fast WDRC over Slow WDRC, when combined with a Strong DNR at a favorable (8 dB) SNR.

Surprisingly, there was no effect of FC on signal fidelity and listeners' preferences. This is contrary to expectations because FC can result in drastic changes in the signal by reintroducing the high-frequency portions of the signal into the listener's audible range and altering the lower frequency vowel formant information and consonant–vowel transitions, thereby affecting intelligibility and sound quality (Alexander, 2016; Alexander et al., 2014; Arehart et al., 2013; McDermott, 2011; Souza et al., 2013). Most of the previous research involving FC was conducted with aggressive settings with very low start frequencies (ranging from 1 to 3 kHz), which can result in significant deviations of the speech envelope and frequency content from the original signal (Alexander & Rallapalli, 2017; Rallapalli & Alexander, 2015; Souza et al., 2013, 2019; Souza, Arehart, Shen, et al., 2015). In this study, clinically realistic settings were used with relatively higher start frequencies (> 4 kHz) determined based on the audiometric configuration of participants. While these participants typically do not require FC, the settings tested in this study reflect a realistic situation where some hearing aid manufacturers leave the FC algorithm ON by default. The lack of preference for such milder FC settings is supported by studies that have reported no detrimental effects of nonlinear FC for speech intelligibility in noise (Miller et al., 2016; Parsa et al., 2013). Finally, in this study, the use of sentence materials rather than consonants may have also resulted in less sensitivity to the effects of FC (Glista & Scollie, 2018).

Listener's preferences are only partly supported by the acoustic analyses. At both SNRs, although signal fidelity with Fast WDRC was poorer than that with Slow WDRC in the presence of Mild DNR, there was no significant difference in preference between the two "Hearing Aid" settings. However, in the presence of Strong DNR, the detrimental effect of Fast WDRC on signal fidelity was reduced, supporting the higher preference for Fast WDRC over Slow WDRC when combined with Strong DNR. The signal fidelity metric did not show any differences between FC ON and FC OFF, suggesting no significant detrimental effects on the envelope of the signal, which appears to be reflected in listeners' preferences.

Limitations and Future Directions

There are a few limitations to this study. First, the study did not measure intelligibility or quality outcomes for the hearing aid signal processing algorithm presented to the listener. While it is possible to speculate about conditions under which intelligibility and quality may have had an influence on preference based on evidence from previous research, a conclusive inference about this relationship cannot be drawn at present. Furthermore, the study did not address individual variability in outcomes across listeners. Factors such as age, cognitive abilities, and peripheral auditory abilities are known to influence both intelligibility and quality outcomes with hearing aids (Souza, Arehart, & Neher, 2015). However, this study was a first step to determine overall preferences for listeners with multiple forms of signal processing present in hearing aids and therefore did not include other related outcomes. Future studies will be designed to measure speech intelligibility and quality under these conditions and to characterize individual variability in relation to listeners' preferences.

Second, several participants provided anecdotal reports that the paired-comparison task was difficult. This is reflected in the fact that while the results showed significant effects of DNR and WDRC on signal fidelity and preference, the odds of preferring one combination over another were still relatively small (closer to 1). Moreover, the post hoc analyses for the ME-BT factorial model at 8 dB SNR did not show any effects of WDRC at each level of DNR. Therefore, further investigation is needed to determine what constitutes "clinically significant" odds of preferring combinations of certain algorithms and parameters over others. There may be a few reasons for these small effect sizes. The clinically realistic settings used in this study may have resulted in subtle differences between "Hearing Aids." Furthermore, when combined with background noise in a simulated spatialized environment, it may have been harder to perceive the differences due to interference from top–down processing such as attention (e.g., Dai et al., 2018).

Third, although the signals were spatialized to approximate realistic listening, use of hearing aid simulation and headphones does not exactly recreate everyday listening conditions; for example, this setup does not account for the effects of external ear acoustics or is not generalized to every type of commercial algorithm. However, since this was the first study to evaluate preferences for a combination of hearing aid signal processing settings using the conjoint analysis framework, it allowed for necessary experimental rigor. Moreover, the use of a hearing aid simulator provided the ability to make comparisons across all possible combinations of hearing aid algorithms and settings, which would have been practically difficult to accomplish with a wearable device.

Fourth, the study and the results are limited to one type of listening condition, which is speech-in-babble noise. The SNRs and the use of multiple talkers are realistic,

but hearing aid users are exposed to other types of noises such as traffic noise, kitchen noise, and reverberation. Future work must consider the effects of other noise types and reverberation because there may be interactions with hearing aid algorithms, as well as different preferences under these conditions (Lundberg et al., 2020; Reinhart et al., 2016).

From a clinical standpoint, the study findings ~~may~~ encourage audiologists to pay attention to fine-tuning WDRC and DNR settings together during hearing aid fitting and follow up appointments rather than relying on manufacturer defaults for these algorithms (Anderson et al., 2018). This may improve how the patient perceives their hearing aid function in noisy situations, which, in turn, is directly related to hearing aid satisfaction (Abrams & Kihm, 2015). However, audiologists must also be cautious in making minor adjustments to hearing aid settings in the clinic based on nonsystematic patient feedback, because a placebo effect is likely to occur rather than a true preference for a setting (e.g., Caswell-Midwinter & Whitmer, 2020; Durkin et al., 2019). Furthermore, the design of this study differs from a typical clinical scenario where patients are provided with a trial period or a period of acclimatization to new settings. Such a period of acclimatization may have an influence on the patient's preference for hearing aid algorithms (e.g., Dawes & Munro, 2017), and this aspect was not captured in this study.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author (Varsha Rallapalli) upon reasonable request.

Acknowledgments

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