Modeling the Relationship Between Listener Factors and Envelope Fidelity: A Pooled Analysis Spanning a Decade

Varsha Rallapalli,[1] Jeffery Crukley,[2,3,4] Emily Lundberg,[5] James M. Kates,[5] Kathryn Arehart,[5] and Pamela Souza[6,7]

Objectives: There is a large variability in speech intelligibility with hearing aids. This variability remains despite the current clinical approaches that provide individualized frequency-specific adjustments to gain in hearing aids. Much of this variability documented in the literature may also be due to differences across studies in terms of outcome measures, test conditions, etc. The objective of this study was to model sources of individual variability in speech intelligibility with hearing aids, in a pooled analysis across four distinct studies that used common methodologies and outcome measures.

Design: Deidentified data from 80 unique listeners with bilateral mild to moderately severe sensorineural hearing loss and aged 49 to 92 years were pooled from four published studies. A hierarchical Beta-Binomial (generalized linear mixed-effects) model was implemented to estimate the probability of correct word recognition in the pooled data using a Bayesian framework. Across studies, word recognition was measured for low-context sentences, in multi-talker babble, for a range of signal to noise ratios. Signals were processed through a hearing aid simulator or a wearable device and were customized to the listener's audiogram. Individual studies involved systematic manipulations of wide dynamic range compression, frequency lowering, or microphone directionality. Individual working memory ability was measured using the reading span test. A well-established auditory metric was used to quantify cumulative envelope fidelity (cepstral correlation) from background noise and the hearing aid processing for each listener.

Results: The model showed a strong relationship between speech intelligibility and envelope fidelity, confirming previous research findings that higher envelope fidelity was associated with better speech intelligibility. Among the sources of individual variability, working memory had a significant effect on the relationship between speech intelligibility and envelope fidelity. Listeners with higher working memory had significantly better word recognition than those with lower working memory, especially when envelope fidelity was worse. In addition, listeners with lower working memory had better word recognition as envelope fidelity increased. Age and degree of hearing loss (four-frequency pure-tone average) did not have a significant effect on the relationship between speech intelligibility and envelope fidelity.

Conclusions: The analysis of the pooled dataset identified sources of individual variability in aided speech intelligibility, while also overcoming limitations of smaller sample sizes in prior research. The model supported the hypothesis that speech intelligibility is affected by the cumulative envelope fidelity arising from a combination of background noise and hearing aid processing. The study findings indicate that individual variability in speech intelligibility with hearing aid processing is related to working memory after accounting for age and degree of hearing loss. The study highlights the need for individualized treatment of hearing loss beyond the pure tone audiogram. Auditory metrics such as the envelope fidelity metric used in the study may be useful tools in clinical decision-making.

Key words: Age, Hearing aids, Signal processing, Working memory.

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INTRODUCTION

Common hearing aid processing features include wide dynamic range compression (WDRC), single-channel or microphone-based digital noise reduction (DNR), and frequency lowering (Ricketts et al. 2019). These features aim to improve listener access to speech sounds by increasing audibility of the target speech and/or reducing the background noise. The strength of these features can be controlled with manufacturer-specific settings to adjust their intended effects. For example, faster WDRC speeds improve speech audibility at the syllabic or phonemic level and in fluctuating noises (Souza & Turner 1999; Kowalewski et al. 2018). Lower start frequencies and higher compression ratios in frequency lowering increase the audibility for high-frequency sounds (McDermott 2011; Souza et al. 2013; Alexander 2016). More gain reduction or filtering in DNR results in greater attenuation of the noise (Bentler & Chiou 2006; Hoetink et al. 2009; Brons et al. 2015), and a narrower directional processing beam results in substantial background noise reduction and improved focus on the target speech signal (Picou & Ricketts 2019).

While stronger feature settings are effective at increasing audibility or reducing background noise, they can also modify cues that carry important information for speech intelligibility. For example, faster WDRC can distort the temporal envelope, especially for the noisy speech signal (Jenstad & Souza 2005; Souza et al. 2006; Stone & Moore 2007). Lower start frequencies and higher compression ratios in frequency lowering may reduce high-frequency formant spacing and distort consonant-vowel transitions (Alexander 2016; Alexander & Rallapalli 2017). Aggressive gain reduction in DNR can remove speech that is overlapping with noise and distort the temporal envelope (Kim & Loizou 2011; Arehart et al. 2015; Rallapalli et al. 2022), whereas narrower directional processing is known to degrade spatial cues necessary for localization and stream segregation (Picou et al. 2014; Best et al. 2015). These tradeoffs in the acoustic signal can affect speech intelligibility and offset the benefits of improved audibility or reduced background noise for listeners.

[1]Department of Communication Sciences & Disorders, University of South Florida, Tampa, Florida, USA; [2]Data Science and Statistics, Toronto, Ontario, Canada; [3]Department of Speech-Language Pathology, University of Toronto, Toronto, Ontario, Canada; [4]Department of Psychology, Neuroscience, and Behavior, McMaster University, Hamilton, Ontario, Canada; [5]Speech Language and Hearing Sciences, University of Colorado Boulder, Boulder, Colorado, USA; [6]Department of Communication Sciences & Disorders, Northwestern University, Evanston, Illinois, USA; and [7]Knowles Hearing Center, Northwestern University, Evanston, Illinois, USA.

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In addition to the independent effects of each hearing aid feature, there can be interaction effects when features are activated simultaneously. These interactions may have positive or negative consequences on the speech signal. For example, the combined effect of noise reduction and fast-acting WDRC may mitigate temporal envelope distortion in the noisy speech signal. This combination of features has resulted in lower annoyance levels, lower acceptable noise levels, and higher preference for strong DNR settings (Wu & Stangl 2013; Rhebergen et al. 2017; Rallapalli et al. 2022; Yun et al. 2024). Directional processing can decouple the speech from noise and result in less temporal envelope distortion caused by hearing aids with fast-acting WDRC (Rallapalli et al. 2021). On the other hand, fast-acting WDRC when combined with frequency lowering adds to the overall distortion of the envelope in the speech signal and can reduce speech intelligibility (Souza et al. 2015, 2019; Alexander & Rallapalli 2017). Thus, it is important to consider the cumulative benefits and changes to envelope fidelity caused by multiple hearing aid features that are acting on the noisy speech signal concurrently (Anderson et al. 2009).

Our approach has been to quantify the cumulative effects of hearing aid processing using auditory metrics; specifically, the Hearing Aid Speech Quality Index (HASQI; Kates & Arehart 2014b) or the Hearing Aid Speech Perception Index (HASPI; Kates & Arehart 2014a, 2021). These two metrics measure changes in envelope modulation (cepstral correlation), temporal fine structure, and long-term spectrum. Specifically, cepstral correlation compares the degraded signal to a reference signal after both signals have passed through models of the impaired auditory periphery, with the reference signal receiving linear amplification to provide distortion-free compensation for the hearing loss. The cepstral correlation term is affected by background noise and hearing aid processing. The resulting metric value ranges from 0 to 1, with a value of 0 indicating no correlation between the degraded and reference signals and a value of 1 indicating a perfect match. In general, cepstral correlation decreases (i.e., envelope distortion increases) as the background noise level increases and hearing aid features such as WDRC, DNR, and frequency lowering are made stronger. Because cepstral correlation can be used to analyze hearing aid output at ear level (Rallapalli et al. 2020), it captures the cumulative effects of hearing aid processing and background noise in a way that represents how a listener hears the signal. Several studies have shown that cepstral correlation is a strong predictor of speech intelligibility for listeners with hearing loss, in a variety of background noise types and hearing aid features making this metric a very useful tool for quantifying acoustic effects across studies using different test conditions (Neher 2014; Arehart et al. 2015, 2022; Souza et al. 2015, 2019; Rallapalli et al. 2021, 2025). Throughout this paper, we will use the more general term "envelope fidelity" to refer to the cepstral correlation value. Lower envelope fidelity indicates lower cepstral correlation or values closer to 0.

Individual Variability

While it is generally expected that lower envelope fidelity due to background noise and hearing aid processing results in poorer speech intelligibility, it is of interest to model how this relationship varies by individual listener factors that are also known to play a role in speech-in-noise intelligibility. Among individual listener factors, working memory (cognition) has been identified as a key variable affecting speech intelligibility in noise, albeit with mixed findings reported in response to hearing aid processing (Cox & Xu 2010; Ng et al. 2014; Souza et al. 2015; Ng & Rönnberg 2020). Working memory is a limited-capacity system that involves simultaneous storage and processing of speech information (Baddeley 2003). As theorized by the Ease of Language Understanding model, working memory is engaged under suboptimal listening conditions (e.g., noise, reverberation) to help overcome the mismatch between the distorted input signal and stored phonological representations in the long-term memory (Rönnberg et al. 2013, 2021). Individuals with a higher capacity have good speech intelligibility even in challenging conditions because they can overcome the mismatch or distortions efficiently (Rönnberg et al. 2010; Rudner et al. 2011). In contrast, those with a lower working memory capacity are at a greater disadvantage under challenging listening conditions (such as background noise, reverberation, and/or hearing aid processing that cause lower envelope fidelity (Reinhart et al. 2016, 2019).

A series of independent studies have consistently shown these relationships with WDRC processing in hearing aids. Specifically, individuals with higher working memory benefited from fast-acting WDRC (relative to slow-acting WDRC), whereas individuals with lower working memory had poorer speech intelligibility with fast-acting WDRC (Gatehouse et al. 2006; Rudner et al. 2009; Souza & Sirow 2014). The detrimental effects of fast-acting WDRC were particularly evident in fluctuating background noises, at lower signal to noise ratios (SNRs) (Lunner & Sundewall-Thorén 2007; Ohlenforst et al. 2016), with low-context sentence recognition tasks (Cox & Xu 2010), and for hearing aid users with less device experience (Ng & Rönnberg 2020). However, the effect of working memory has been less consistent with other forms of hearing aid processing, with some studies showing a weaker role of working memory in response to DNR processing, frequency lowering, and different microphone modes (Ellis & Munro 2013; Keidser et al. 2013; Souza et al. 2015).

One of the challenges in drawing inferences across independently conducted studies is the variability in experimental paradigms. Methodological differences, such as the type of speech, the background noise characteristics, or the population tested (e.g., listeners with normal hearing vs. hearing loss), can significantly impact the results (see Dryden et al. 2017 for review). There is also considerable variation in how hearing aid processing is implemented due to the choice of different manufacturers and their device features within each study. Earlier studies used two-channel hearing aids (Gatehouse et al. 2006; Lunner & Sundewall-Thorén 2007) whereas more recent studies used hearing aids with 20 or more channels (Souza et al. 2019; Rallapalli et al. 2021). Hearing aid models also vary greatly in the range of WDRC speeds (attack and release times) and DNR strength available in the device (Bentler & Chiou 2006; Scollie et al. 2016; Rallapalli et al. 2018), which may have affected the envelope fidelity received by listeners across hearing aid processing in different studies (Kates et al. 2018; Rallapalli et al. 2020). Consequently, studies that analyzed the effect of different hearing aid feature settings as categorical variables may not necessarily capture the extent of distortion introduced in the signal.

While considering sources of individual variability, a series of six studies over the past decade found that working memory

TABLE 1. Summary of key findings from studies examining the relationship between envelope fidelity and individual listener variables: WM, age, and degree of hearing loss (PTA) on speech intelligibility

Study	Processing Conditions	Envelope Fidelity	WM	Age	Degree of Hearing Loss (PTA)
Arehart et al. (2013)	Babble + FC	Lower envelope fidelity with stronger FC (lower start frequencies, higher compression ratios) and higher babble levels	WM explained 29.3% of variance in speech intelligibility; poorer intelligibility at lower envelope fidelity levels for the lower WM group	Not a significant predictor after controlling for WM and PTA	Controlled for in the analysis; not a primary predictor
Souza et al. (2015)	Babble + WDRC (fast vs. slow) and FC (Off, mild, strong)	Lower envelope fidelity with faster WDRC, stronger FC (lower start frequencies, higher compression ratios), and higher babble levels	Poorer intelligibility with lower envelope fidelity	Not specifically highlighted	Effect of lower WM on intelligibility was stronger in listeners with more severe hearing loss (greater PTA)
Arehart et al. (2015)	Babble + varying amounts of noise suppression (ideal binary masking)	Lower envelope fidelity with more errors in noise suppression and higher babble levels	WM significantly predicted intelligibility; combined with PTA, explained 46% of variance	Not significant	Significant predictor of intelligibility, combined with WM
Souza et al. (2019)	Double-blind trial: babble + mild (slow WDRC and FC Off) vs. strong (fast WDRC and FC ON) processing	Lower envelope fidelity with stronger processing settings	Individuals with lower WM were less likely to benefit from mild processing	Older adults had progressively poorer recognition with lower envelope fidelity	Individuals with greater PTA had poorer recognition with lower envelope fidelity
Rallapalli et al. (2021)	Spatially separated babble + microphone mode (omnidirectional vs. directional) + WDRC speed (fast vs. slow)	Lower envelope fidelity with faster WDRC, omnidirectional mics, higher babble levels; significant interaction between WDRC and microphone mode	WM was positively associated with intelligibility; effect was strongest when envelope fidelity was high (directional mics, higher SNR)	Co-varied with WM; could not control for in analysis	Controlled for in analysis; not a primary predictor
Rallapalli et al. (2025)	Spatially separated babble + microphone mode (omnidirectional vs. beamformer) + WDRC speed (fast vs. slow)	Lower envelope fidelity with faster WDRC, omnidirectional mics; no interaction between WDRC and microphone mode	WM was positively associated with intelligibility; Effect was strongest when envelope fidelity was high (beamformer, higher SNR)	Controlled for in analysis; not a primary predictor	Controlled for in analysis; not a primary predictor

FC, frequency compression (a form of frequency lowering; Off, mild, and strong levels are as designated in the published studies); PTA, pure-tone average; WDRC, wide dynamic range compression; WM, working memory.

was associated with speech intelligibility in noise, in response to systematic changes in envelope fidelity with different hearing aid features such as WDRC, DNR, frequency lowering, or microphone mode. The key findings from these six studies are summarized in Table 1. Some of these studies analyzed the relative contributions of individual variables such as age and degree of hearing loss and found that susceptibility to lower envelope fidelity (i.e., reduced speech intelligibility) was compounded for older adults and those with more severe hearing losses. Notably, however, the degree of interaction between the individual listener variables (age, working memory, and degree of hearing loss) and envelope fidelity, as well as their independent contributions to speech intelligibility, varied across the studies. In addition, while the effect of working memory was significant in all studies, about half the studies found that individuals with higher working memory showed greater improvement in speech intelligibility in favorable listening conditions (higher envelope fidelity) than those with lower working memory (Souza et al. 2019; Rallapalli et al. 2021, 2025). This was opposite to the expected direction of the working memory effect reported in previous literature. Thus, while there is evidence that working memory plays a significant role in understanding variability in hearing aid outcomes, the exact nature of the relationship, along with the relative contributions of age and degree of hearing loss, is not fully understood.

Purpose

Our goal was to build a model to understand the multifaceted nature of speech intelligibility in noise with hearing aids, which considers a listener's hearing abilities, cognitive abilities, and age. We addressed two questions in our model:

1. What is the relationship between speech intelligibility and envelope fidelity?

2. To what extent do previously identified sources of individual variability (working memory, age, and degree of hearing loss) modify this relationship?

To provide a unifying approach to capture the listener's response to various sources of envelope distortion including hearing aid features (regardless of type), background noise, and hearing loss, we pooled data from studies that quantified envelope fidelity using cepstral correlation from the HASQI metric. The HASQI cepstral correlation term has been shown to be strongly correlated with the lower-rate envelope modulation used in the HASPI v2 intelligibility metric (Kates & Arehart 2021). We considered this to be a reasonable approach to characterizing variability in hearing aid outcomes, while minimizing discrepancies due to test conditions and increasing the power to detect effects of interest.

The speech intelligibility data collected across the individually published studies used Institute of Electrical and Electronics Engineers (IEEE; Rothauser 1969) sentences containing five target words, with performance measured as the number of correctly identified words per sentence. These data are naturally suited to binomial modeling because they represent discrete outcomes within a fixed number of trials. While previous studies have commonly applied linear models to percent correct scores, we consider a more appropriate and statistically robust binomial approach in this pooled analysis. Unlike percent correct scores—which are bounded between 0 and 100 and may violate assumptions of continuity and homoscedasticity—binomial models respect the discrete and bounded nature of the data, enabling more accurate estimation and inference (Kruschke & Liddell 2018).

MATERIALS AND METHODS

Criteria for inclusion of study data in the model included availability of a common outcome measure (word-level scores for IEEE sentences), envelope fidelity measures, and common measures for individual listener variables (full version of the Reading Span Test [RST], age, and four-frequency pure-tone average [PTA] at 0.5, 1, 2, 4 kHz). Out of the six studies in this series, the final dataset contained pooled data from four studies that met these criteria. Data from two studies were excluded from the pooled analysis due to methodological discrepancies. Specifically, data from Rallapalli et al. (2025) were excluded from the analysis because the study measured working memory using an abbreviated version of the RST, which would have resulted in a different range of working memory scores than the studies that used the longer version of the test. Data from Arehart et al. (2015) were excluded from the analysis due to a lack of word-level data for binomial modeling. Methodological details for the studies included in this pooled analysis are summarized in Table 2. The individual study data reviewed by the authors for inclusion in the analysis were previously deidentified. A brief description of listener characteristics and test conditions in the final dataset is included later.

Listener Demographics

To enable binomial modeling at the trial level, the pooled analysis included only listeners with available word-level response data, allowing for more granular and statistically appropriate analysis. This resulted in 80 unique listeners across the four studies. Data were from listeners with symmetric, bilateral, mild to moderately severe sensorineural hearing loss with average four-frequency PTA for both ears ranging from 10 to 61 dB HL (M = 34.69, SD = 12.95). Listeners were older adults, with ages ranging from 49 to 92 years (M = 72.05, SD = 8.45), with a roughly equal representation of males and females.

Outcome Measure

In all studies, the outcome measure was speech intelligibility in multi-talker Connected Speech Test babble (CST; Cox et al. 1987). Target sentences were from the IEEE database and were spoken by a single female talker. The exception was Rallapalli et al. (2021), which included multiple male and female talkers from a local-talker database (Panfili et al. 2017) for the generalizability of findings. Target sentences were always presented at a conversational level of 65 dB SPL. Across studies, multi-talker CST babble consisted of either 4, 6, or 8 talkers, and the SNRs ranged from −10 to +10 dB. All studies except Souza et al. (2019) included a quiet (no babble) condition. There were minor differences across studies in how the stimuli were delivered to the listener and the spatial configuration of speech and babble, as summarized in Table 2.

In all studies, the listeners' task was to repeat the target sentence as best as they could. An experimenter scored the number of correctly repeated key words for each sentence. The order of sentence lists and test conditions were randomized across listeners within a study.

Hearing Aid Processing

Hearing aid signal processing was presented through a hearing aid simulator or wearable (commercially available) hearing aids. The simulator provides a high level of experimental control, while the wearable hearing aids are representative of clinical conditions.

Hearing Aid Simulator • A full description of the hearing aid simulator is available in (Arehart et al. 2013) and Souza et al. (2015). The basic architecture comprised a multichannel filter bank, followed by independent noise suppression and WDRC in each frequency band. A frequency compression stage was then applied to the WDRC outputs summed across bands. The simulator modeled an occluded hearing aid fitting with no venting or ear canal resonance (e.g., headphone stimulus presentation), and the hearing aid output was not verified in individual ears. Hearing aid processing was adjusted using an array of processing parameters, and processing stages not needed for a particular experiment were bypassed (e.g., noise suppression).

The audiogram was specified at the six audiometric frequencies of 250, 500, 1000, 2000, 4000, and 6000 Hz. The number of hearing aid frequency bands was six, and the band center frequencies matched the audiometric frequencies. The filterbank used a linear-phase finite impulse response design so the outputs in all bands were temporally aligned. The WDRC processing in Arehart et al. (2013) and Souza et al. (2015) used a 45 dB SPL lower compression threshold and a 2:1 compression ratio in all frequency bands. The RMS power in each band was then matched to the power in the original unprocessed signal

TABLE 2. Summary of listener characteristics and test conditions across four studies in the pooled analysis

Study	No. of Listeners	Age (yrs)	RST%	PTA (dB HL)	SNR (dB)	Noise Locations	Hearing Aid Type	Hearing Aid Processing
Arehart et al. (2013)*	12	63–80	27.8–59.3	10–39	−10, −5, 0, +5, +10, quiet	0°	Simulator, headphones, monaural presentation	WDRC: Linear FC†: Off; 2, 1.5, 1 kHz SF; 3:1, 2:1, 1.5:1 CR Mic: Omni
Souza et al. (2015)*	10	49–86	24–50	33–50	0, +10, quiet	0°	Simulator, headphones, monaural presentation	WDRC: Linear, 40 and 640 msec RT FC: Off, 1.5 SF 3:1 CR, 2 kHz SF 2:1, CR Mic: Omni
Souza et al. (2019)‡	40	54–90	11–55.6	29–61	0, +5, +10	0°	Commercial device, binaural BTE RIC with vented earmolds	WDRC: 59 and 6900 msec RT FC: Off, 2.1 kHz SF 2.67:1 CR Mic: Omni
Rallapalli et al. (2021)	23	59–92	22.2–57.4	23–57	0, +5, +10, quiet	90°, 180°, 270°	Commercial device, binaural BTE RIC with vented earmolds	WDRC: 70 and 4000 msec RT FC: Off Mic: Omni, Fixed Dir

Linear FC applied above SF.†SFs and CRs were fully crossed.‡Nonlinear FC applied above SF.BTE, behind-the-ear; CR, compression ratio; FC, frequency compression (a form of frequency lowering); Mic, microphone mode (omnidirectional or omni, directional or dir); RIC, receiver-in-the-canal; RST, reading span test; RT, release time; SF, start frequency; SNR, signa to noise ratio; WDRC, wide dynamic range compression.

to remove any long-term gain changes caused by the compression, and NAL-R equalization was then applied to the signals to provide individualized spectral contours appropriate for the audiograms. The compressor attack and release times used in the present experiments are listed in Table 2. A given time constant was the same in all frequency bands.

The frequency compression algorithm was based on sinusoidal modeling of the speech signal, in which the signal was represented by a set of dynamically varying sinusoidal components (Arehart et al. 2013). The algorithm first passed the speech through a complementary lowpass-highpass filter pair; the output of the lowpass filter was used without any modification, while the high-frequency output was lowered in frequency. The high-frequency output was divided into overlapping 6-msec segments, and the 10 highest-amplitude peaks were identified in each segment. The 10 peaks were then reproduced keeping the amplitude and phase unchanged while shifting the frequencies lower. The processing parameters were the cutoff frequency of the highpass-lowpass filter pair and the linear frequency compression ratio applied to the high frequencies.

Wearable Hearing Aids • In Souza et al. (2019) and Rallapalli et al. (2021) amplification was provided with commercially available multichannel behind-the-ear devices from two different manufacturers, coupled with earmolds to maximize the effects of signal processing and gain (Winkler et al. 2016) as well as to minimize any feedback. A small vent was provided for ventilation purposes. Both hearing aids allowed the experimenter to program the specific hearing aid feature settings, including WDRC speed, frequency lowering strength, and microphone modes. In both studies, individualized frequency-specific gain compensation was based on the NAL-NL2 prescriptive method (Keidser et al. 2011) and was verified using the real-ear aided response, according to clinical best practices (Valente et al. 2006).

Specific hearing aid feature settings manipulated within a study are presented in Table 2. As a reminder, the studies that used the hearing aid simulator applied linear frequency compression to the signals above the start frequency, whereas the study that used the wearable hearing aids applied nonlinear frequency compression. For the purposes of the statistical model, the following criteria were used to group frequency lowering levels based on start frequency and compression ratio: "High" was assigned to lower start frequencies (<2 kHz) with higher compression ratios (2 or 3), "Medium" to start frequencies around 2 kHz with higher compression ratios (2 or 3), and "Low" to higher start frequencies (≥1.5 kHz) with lower compression ratios (<2). A fourth frequency-lowering level included "Off" when no frequency lowering was applied to the signal. The following criteria were used to group WDRC levels based on release times: "Fast" was assigned to release times <250 msec, and "Slow" to release times >250 msec; where applicable, a third WDRC level included "linear" amplification with a compression ratio of 1.

Envelope Fidelity Metric

As described in the Introduction, envelope fidelity was quantified using cepstral correlation (HASQI; Kates & Arehart 2014b). In the two studies that used a hearing aid simulator to process sounds, envelope fidelity was computed for individual stimuli presented to the listener on each trial. In the studies that used wearable hearing aids, envelope fidelity was calculated for recordings obtained from the hearing aids programmed to the individualized settings in each test condition within the study. The recordings were obtained either in a test box (Kates et al. 2018) (simulating an occluded fitting) or an acoustic manikin fitted with earmolds (Rallapalli et al. 2020) for representative pairs of sentences spoken by a male and a female talker. Thus, the envelope fidelity value represents the cumulative effects of hearing aid processing and background noise conditions, including noise levels and temporal characteristics of the babble. As a reminder, an envelope fidelity value closer to 0 represents lower cepstral correlation or greater temporal envelope distortion relative to the reference signal. Across studies, the target sentences used a selection of male and female talkers, with talkers randomly assigned to different IEEE sentences; multiple sentence presentations for each test condition helped normalize the acoustic variability across different sentences.

Reading Span Test

Working memory ability was measured using the RST (Daneman & Carpenter 1980; Rönnberg et al. 1989). RST is designed to capture the ability to coordinate simultaneous processing and storage of information. The test consisted of 3 to 6 sentences, presented one at a time. Words or word pairs were presented at a rate of 0.8 sec per word. The listener was instructed to make a judgment about the meaningfulness of each sentence (processing) and then recall either the first or last words of each sentence in a set (storage). The measure of working memory was the percentage of words recalled correctly, in any order (RST%). The interval between sentences was 1.75 sec. The test was administered in a visual-verbal modality and completed within 10 to 12 min. The average RST in the pooled dataset was 36.44% and SD was 9.54%.

ANALYSIS

We combined speech intelligibility data generated with IEEE sentences from four studies (80 unique listeners) to conduct our pooled analysis. We implemented a hierarchical Beta-Binomial (generalized linear mixed-effects) model to estimate the probability of correct word recognition using our pooled data under a Bayesian framework. The statistical approach used in this study was appropriate for the binomial word recognition data.

The model included envelope fidelity, age, four-frequency PTA, RST%, and the interactions between envelope fidelity and RST%, envelope fidelity and age, and envelope fidelity and PTA as population-level effects. Previous studies showed that factors in the listening environment as well as hearing aid features, can have independent effects on speech intelligibility (Table 1). To control for these effects, the model also included SNR, spatial condition, WDRC, frequency lowering, microphone mode, and the interactions between envelope fidelity and WDRC, envelope fidelity and frequency lowering, and envelope fidelity and SNR. The SNR levels in the model included a realistic range as reported in recent literature from 0 dB to Quiet (Smeds et al. 2015; Wu et al. 2018). We included varying effects for listener, primary authors, years within primary authors, and the correlation between SNRs and envelope fidelity within each listener. We used skeptical, regularizing priors for model parameters: standard normal for the model intercept, cepstral correlation coefficient, and author-level varying effects; Normal (0,0.5) for all other coefficients; Normal (1,1) for subject-level varying effects, Weibull (5,3) for the precision parameter (phi), and LKJ (1) for correlation matrices. The estimate for phi was 4.35 [4.07, 4.64]. We implemented the model using the Stan probabilistic programming language (Carpenter et al. 2017) through the cmdstanr package (Gabry & Češnovar 2021) in R statistical computing software (R Core Team 2022). Figure 1 is a schematic illustration of the statistical model.

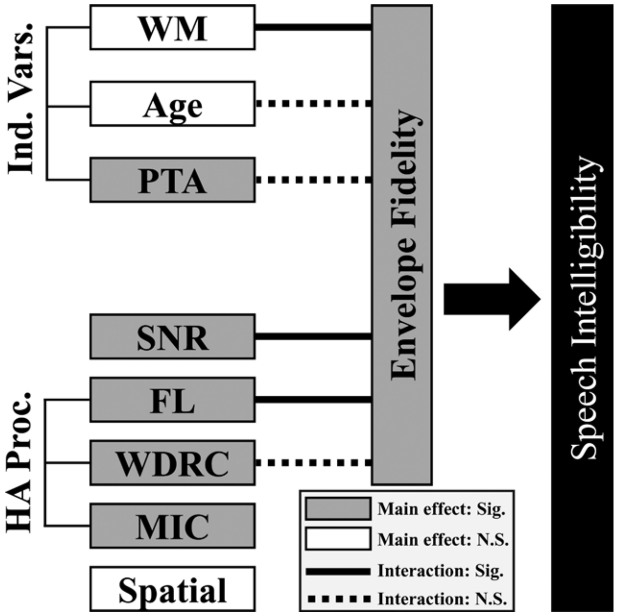

Fig. 1. Schematic representation of the statistical model of the relationship between envelope fidelity and speech intelligibility outcomes. Moderating factors include individual variables (Ind. Vars.: WM, age, PTA), SNR, and hearing aid processing (HA Proc.: Frequency lowering or FL, WDRC, MIC), as well as spatial condition (Spatial). Gray-shaded boxes indicate significant (Sig.) main effects, while white boxes represent NS main effects. Solid lines indicate significant (Sig.) interactions between factors; dashed lines indicate NS interactions. FL indicates, frequency lowering; MIC, microphone mode; NS, nonsignificant; PTA, pure-tone average; SNR, signal to noise ratio; WDRC, wide dynamic range compression; WM, working memory.

RESULTS

We fit our model to the data with four parallel chains of 1000 warmup and 1000 sampling iterations. The resulting fit of our model to the data resulted in no divergences, R-hat estimates of 1.0 and equivalent sample sizes (of greater than 2000 for all parameters with no divergent transitions. Together, these diagnostics indicate model convergence. As shown in Figure 2, the model captured the observed data well with similar observed and predicted means. We present our results with point estimates (means) and 89% highest-density credible intervals (HDI). An 89% HDI represents the interval or range of values containing 89% of the posterior probability mass for a parameter or estimate. Unlike frequentist confidence intervals, HDIs provide a direct probabilistic statement regarding the estimate and its uncertainty such that there is an 89% probability that the true value lies within this interval, conditional on the model and data. We chose an 89% interval as this value is more stable than 95% (Kruschke 2014) as well as being commonly used in Bayesian analyses. Parameter estimates for which the HDI excludes zero are reported as “statistically significant” in our results.

The purpose of this pooled analysis was to model the relationship between envelope fidelity and speech intelligibility and to identify sources of individual variability in the dataset. We will briefly summarize the results pertaining to the significant effects of SNR, spatial conditions, and hearing aid features, and then focus on primary research questions. Please refer to Table A in Supplemental Digital Content 1, https://links.lww.com/EANDH/B766, for the regression summary.

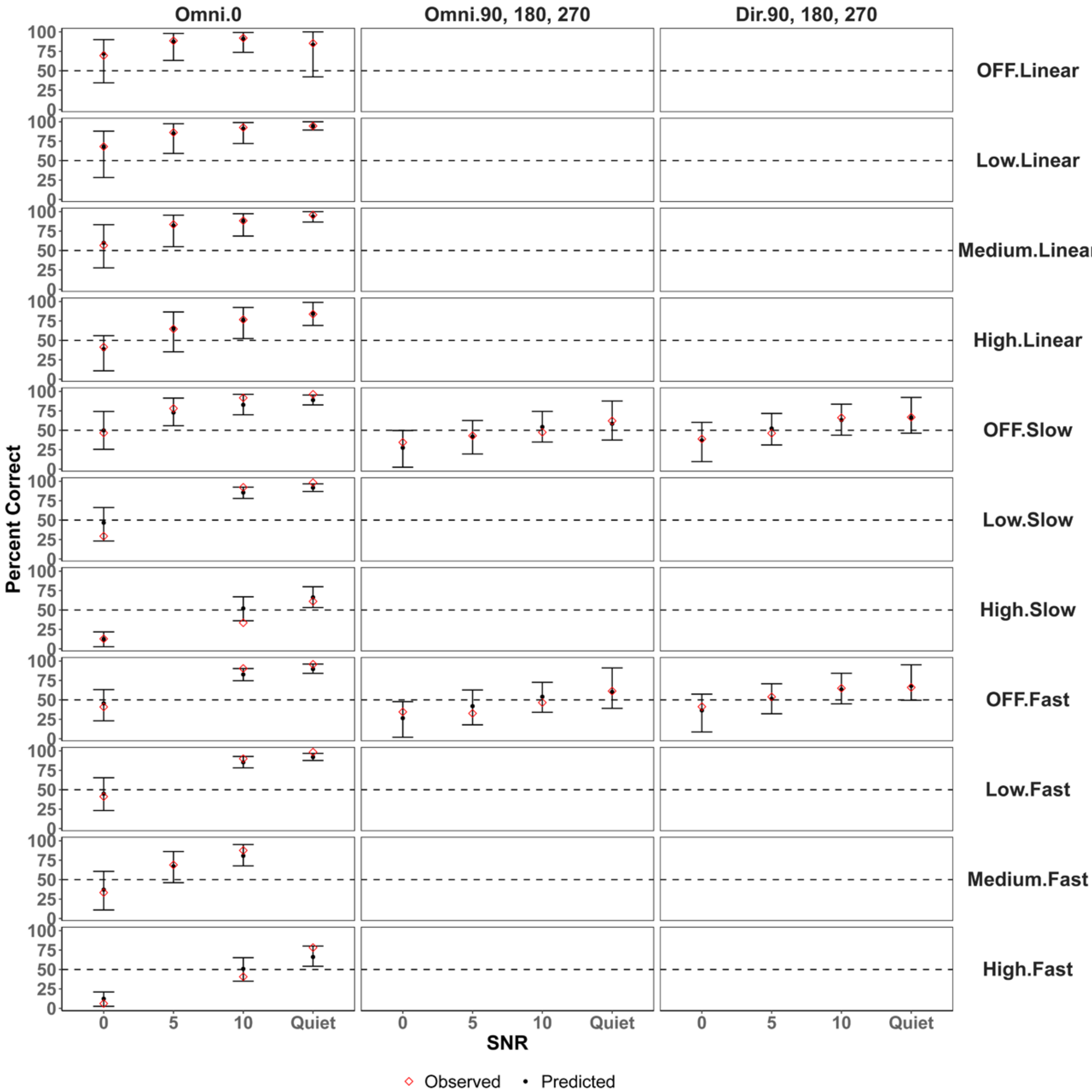

Fig. 2. Comparison between observed and predicted mean percent correct (word recognition) scores across test conditions in the pooled dataset. SNR is represented along the *x*-axis. Microphone mode (Omnidirectional or Omni, Directional or Dir) and spatial condition (0° or 90°,180°, 270°) are represented in the columns. Wide dynamic range compression (Linear, Slow, Fast) and frequency lowering levels (Off, Low, Medium, High) are represented in the rows. Error bars indicate uncertainty in the predicted means as 89% highest-density credible intervals. SNR indicates signal to noise ratio.

Our model showed a significant relationship between envelope fidelity and speech intelligibility in noise such that word recognition increased with higher envelope fidelity (0.46, 89% HDI [0.23, 0.71]). The model showed a significant effect of SNR such that word recognition in the Quiet condition was better than word recognition at 0 dB (−1.19, 89% HDI [−1.46 to −0.90]) and 5 dB (−0.45, 89% HDI [−0.63 to −0.27]) SNRs. The model also showed a significant effect of WDRC such that word recognition with Linear was better than word recognition at Slow (−0.32, 89% HDI [−0.58 to −0.04]) and Fast (−0.31, 89% HDI [−0.57 to −0.05]) WDRC levels. The model showed a significant effect of microphone mode such that word recognition in the directional mode was better than the omnidirectional mode (0.36, 89% HDI [0.19 to 0.53]). The model also showed significant interactions between envelope fidelity and SNR as well as between envelope fidelity and frequency lowering. Specifically, the relationship between envelope fidelity and word recognition was significantly stronger in the Quiet condition relative to 5 dB (−0.18, 89% HDI [−0.33 to −0.04]) and 10 dB SNRs (−0.17, 89% HDI [−0.27 to −0.07]). Similarly, the relationship between envelope fidelity and word recognition was significantly stronger at "Low" (0.19, 89% HDI [0.07 to 0.32]), "Medium" (0.39, 89% HDI [0.21 to 0.58]), and "High" (0.45, 89% HDI [0.29 to 0.61]) levels of frequency lowering compared with "Off."

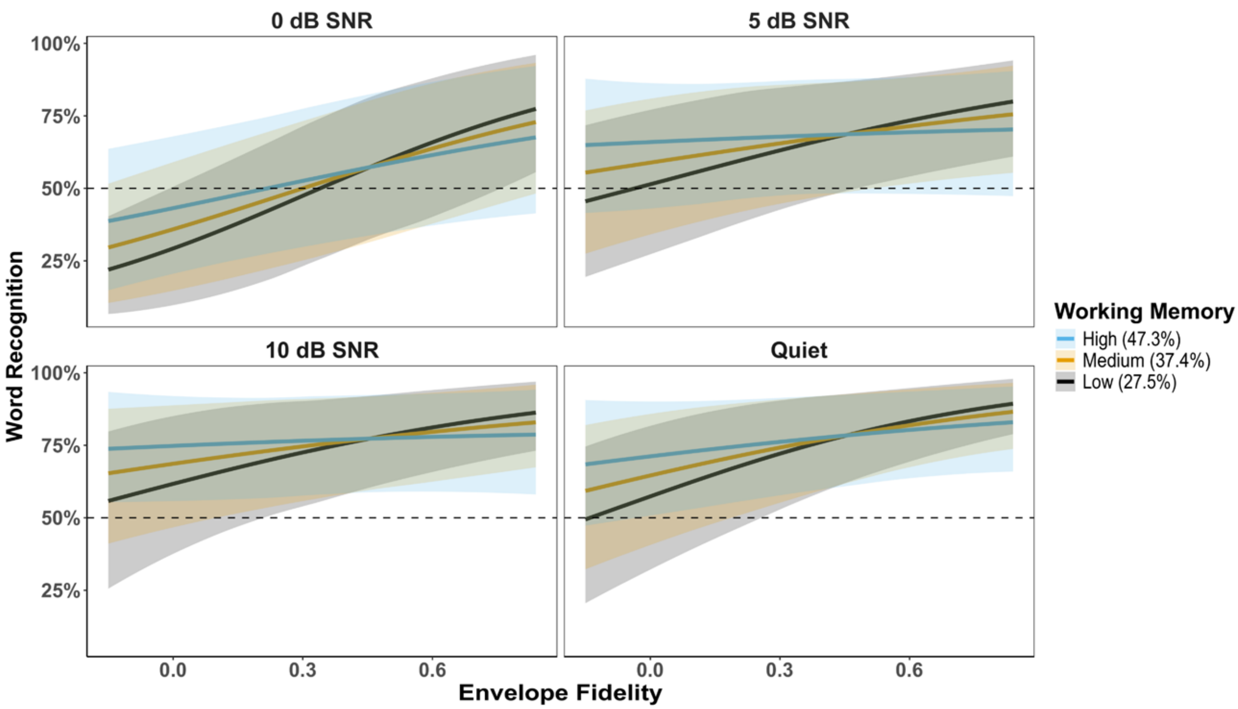

Fig. 3. Prototypical plots of the relationship between envelope fidelity (*x*-axis; 0 = lowest) and word recognition ability (%; *y*-axis) at three levels of working memory based on quantiles (Low or 25th percentile: 27.5%, Medium or 50th percentile: 37.4%, High or 75th percentile: 47.3%). Shaded areas show the 89% highest-density credible intervals at each level of working memory.

Sources of Individual Variability

We examined three sources of individual variability in our model, including working memory, PTA, and age, and describe the conditional effects below, modeled at fixed levels for other variables.

Working Memory • We modeled working memory scores as continuous; however, to facilitate interpretation and visualization of interaction effects, we used quantiles of the observed scores to create three levels/groups: Low (25th percentile of scores: 27.5%), Medium (50th percentile of scores: 37.4%), and High (75th percentile of scores: 47.3%) (Fig. 3). The model showed a significant effect of working memory as a moderator of the effect of envelope fidelity on word recognition (−0.20, 89% HDI [−0.36 to −0.05]). Individuals with lower working memory demonstrated benefit from higher envelope fidelity, whereas individuals with higher working memory did not.

Age • We modeled age as continuous; however, to facilitate interpretation and visualization of interaction effects, we used quantiles of the observed scores to create three levels/groups: Low (25th percentile of scores: 62.8 years), Medium (50th percentile of scores: 71.9 years), and High (75th percentile of scores: 80.9 years) (Fig. 4). The model showed a minimal effect of age on the relationship between envelope fidelity and word recognition (−0.10, [−0.27 to 0.07]). There was also no main effect of age on word recognition ability (−0.07, 89% HDI [−0.22 to 0.07]).

Pure-Tone Average • As with working memory and age, we modeled PTA as continuous. To facilitate visualization of effects, we used quantiles of the observed scores to create three levels/groups: minimal (25th percentile of scores: 23.5 dB), mild (50th percentile of scores: 36.3 dB), and moderate (75th percentile of scores: 49.2 dB) (Fig. 5). The model showed a minimal effect of PTA on the relationship between envelope fidelity and word recognition (−0.11, 89% HDI [−0.31 to 0.10]). The main effect of PTA was as expected, where individuals with moderate loss had the poorest word recognition, whereas individuals with minimal hearing loss had the best word recognition (−1.03, 89% HDI [−1.25 to −0.82]).

DISCUSSION

Our model showed a significant relationship between envelope fidelity and speech intelligibility, confirming previous research findings that higher envelope fidelity is associated with better speech intelligibility (Neher 2014; Arehart et al. 2015, 2022; Souza et al. 2015, 2019; Rallapalli et al. 2021, 2025). In general, the model supported the hypothesis that speech intelligibility is negatively affected by the cumulative envelope distortions arising from a combination of background noise, hearing aid processing, and hearing loss (Anderson et al. 2009). The metric captures nonlinear distortions to the temporal envelope that occur when hearing aid processing interacts with background noise (Souza et al. 2006; Naylor & Johannesson 2009; Alexander & Masterson 2015; Chinnaraj et al. 2021) as well as the interactions that may occur between different hearing aid processing (e.g., noise management and fast-acting WDRC) (Wu & Stangl 2013; Rallapalli et al. 2022; Ellis et al. 2024). This approach is more representative of the "real" scenario in which the listener responds to the overall processed signal, as opposed to studying the effects of background noise and hearing

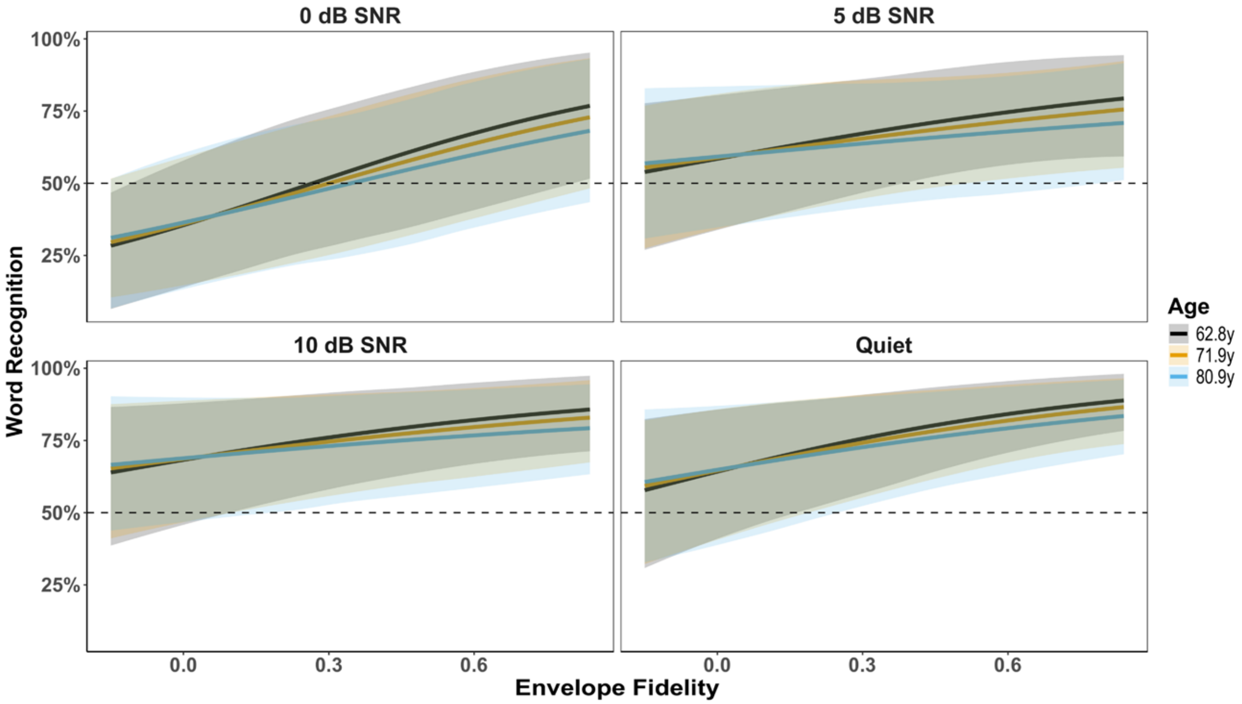

Fig. 4. Prototypical plots of the relationship between envelope fidelity (*x*-axis; 0 = lowest) and word recognition ability (%; *y*-axis) at three levels of age based on quantiles (Low or 25th percentile: 62.8 yrs, Medium or 50th percentile: 71.9 years, High or 75th percentile: 80.9 yrs). Shaded areas show the 89% highest-density credible intervals at each level of age.

aid processing as though they were occurring separately. It is important to note that the model also reveals that speech intelligibility remains strongly associated with envelope distortions in the signal *after* compensating for loss of audibility (i.e., with reference to a linearly amplified signal in quiet).

The individual published studies that generated the component data showed that the relationship between speech intelligibility and envelope fidelity was complex, influenced by various listener variables (Table 1). Across these studies, the impact of working memory on the relationship between envelope fidelity and speech intelligibility was significant. However, the effects of age and degree of hearing loss (PTA) varied, with some studies showing an interaction between PTA and working memory (Arehart et al. 2015; Souza et al. 2015), while one study showed significant independent effects of age, PTA, and working memory on speech intelligibility (Souza et al. 2019). Some of these studies only included these variables as covariates in the statistical model and did not consider their interactions with envelope fidelity (Rallapalli et al. 2021, 2025). In addition, in recent studies that used wearable, multichannel hearing aids (Souza et al. 2019; Rallapalli et al. 2021, 2025), the effects of working memory were contrary to expectations and previous research (Gatehouse et al. 2006; Lunner & Sundewall-Thorén 2007; Souza et al. 2015). Specifically, in these recent studies, test conditions with higher envelope fidelity benefited listeners with higher working memory rather than those with lower working memory. To resolve these discrepancies, we pooled data across these studies and modeled the extent to which the previously identified sources of individual variability affected speech intelligibility in response to the envelope fidelity metric. The pooled analysis identified the relative contributions of working memory, age, and degree of hearing loss, while also overcoming limitations of smaller sample sizes in prior research (Gaeta & Brydges 2020). Furthermore, by analyzing responses to envelope fidelity, the model provided a unified metric to evaluate relationships.

Working memory was a source of individual variability that influenced the relationship between envelope fidelity and speech intelligibility. Listeners with higher working memory performed significantly better than those with lower working memory, especially when envelope fidelity was lower. Listeners with lower working memory had better word recognition as envelope fidelity increased compared with lower levels of envelope fidelity (values closer to 0). These results indicate that while the combination of high background noise (low SNR) and stronger signal processing can be particularly detrimental for listeners with lower working memory, these listeners are more likely to improve their speech intelligibility in conditions with higher envelope fidelity (i.e., more favorable conditions).

Most of the literature, including the Ease of Language Understanding model, supports the significant role of working memory in speech intelligibility under difficult listening conditions (Lunner & Sundewall-Thorén 2007; Rönnberg et al. 2011, 2013, 2021; Heinrich, 2020). Background noise and stronger hearing aid processing—such as fast-acting WDRC and stronger frequency lowering—distort the temporal envelope of the speech signal (Souza et al. 2013; Alexander & Masterson 2015; Varnet & Lorenzi 2022). The temporal envelope carries important information for identifying speech, such as segmental cues for manner of articulation and voicing (Rosen 1992; van der Horst et al. 1999) and cues for recognition of vowels in sentences (Fogerty & Humes 2012; Fogerty 2013). Consequently, when listeners receive a degraded temporal envelope of speech

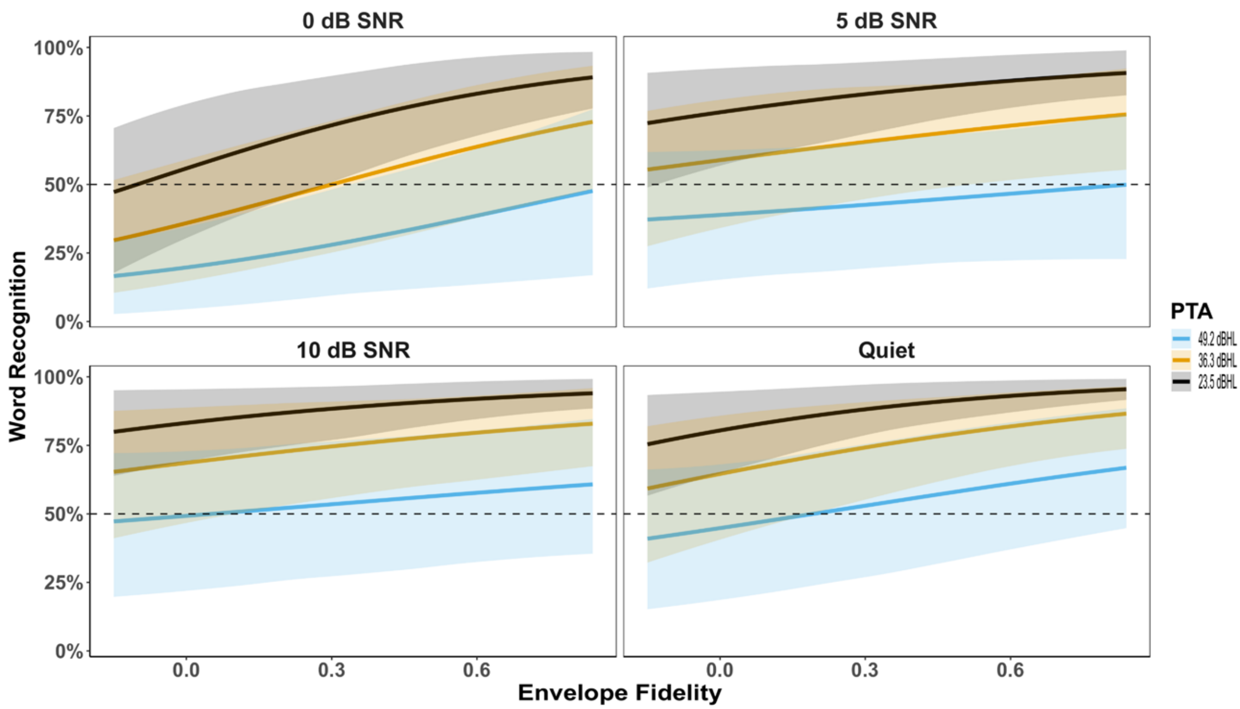

Fig. 5. Prototypical plots of the relationship between envelope fidelity (*x*-axis; 0 = lowest) and word recognition ability (%; *y*-axis) at three levels of hearing loss (four-frequency PTA) based on quantiles (Minimal or 25th percentile: 23.5 dB, Mild or 50th percentile: 36.3 dB, Moderate or 75th percentile: 49.2 dB). Shaded areas show the 89% highest-density credible intervals at each level of PTA. PTA indicates pure-tone average.

that may not match the phonological representations of speech in the brain (Li & Allen 2011) there is increased reliance on working memory resources to compensate for this mismatch. Thus, when the envelope fidelity is lower due to high background noise, listening with stronger hearing aid processing that further distorts the temporal envelope of speech disproportionately reduces speech intelligibility for individuals with lower working memory compared with those with higher working memory. Conditions with higher envelope fidelity (more favorable) are beneficial for listeners with lower working memory because fewer working memory resources may be needed to achieve good speech intelligibility. Conversely, in conditions with higher envelope fidelity, listeners with higher working memory did not show additional improvements in speech intelligibility, likely because their performance was already near optimal. Clinically, this may mean that listeners with lower working memory are more likely to benefit from the appropriate use of microphone directionality or remote microphones in conditions with lower envelope fidelity.

Regarding age, the observed trends in Figure 4 suggest that older adults with hearing loss had worse speech intelligibility than younger adults in conditions with lower envelope fidelity, but the effect of age was not statistically significant in the model. The effects of aging on speech intelligibility have been studied extensively in the literature with mixed findings. For example, some studies have shown independent effects of age on speech intelligibility in noise, after accounting for cognitive abilities (Marsja et al. 2022). Other studies have found that auditory spectro-temporal processing deficits (Grose & Mamo 2012; Füllgrabe et al. 2014; Eddins et al. 2022) and other domain-general cognitive changes (such as processing speed, executive function, inhibition) (Pichora-Fuller et al. 2016; Dryden et al. 2017) may better explain the decrease in speech intelligibility in noise for older adults with hearing loss than age alone. Deterioration of such abilities with age can impact the ability to resolve and process a distorted (or modified) speech signal (Humes et al. 2013; Edwards 2016; Davidson & Souza 2024). However, the rates at which these abilities deteriorate can be highly variable among older adults (Eddins et al. 2018) and warrant further investigations into the effects of auditory and cognitive processing on aided speech-in-noise listening.

After accounting for working memory and age in the model, there was minimal contribution from the listener's degree of hearing loss (measured as four-frequency PTA) to the relationship between speech intelligibility and envelope fidelity. This is not surprising considering that the listeners in the pooled dataset were compensated for audibility loss through well-fit amplification. It is important to note that this supports the argument that audibility alone is not sufficient for achieving optimal speech intelligibility with hearing aids. This finding may partly explain why some listeners with the same audiograms and appropriately fit hearing aids continue to perform poorly, leading to a lack of perceived benefit, especially in noisy conditions (Davidson et al. 2021).

Current clinical approaches to hearing aid fitting primarily focus on restoring audibility. Often, the primary complaint of the patient is that they cannot hear soft sounds, and therefore, improving frequency-specific audibility is an important goal. However, in clinical settings, customization of advanced features, including frequency lowering and noise management, is limited. Recent surveys indicate that audiologists adjust these hearing aid features (which can change envelope fidelity) in three primary ways: relying on manufacturer defaults (which are not based on evidence available in the open literature); using anecdotal experience; and responding to patient complaints (Anderson et al. 2018; Davidson et al. 2022). The relationships revealed in this study indicate that current clinical approaches that focus primarily or exclusively on audibility are inadequate and that a more individualized approach to hearing loss treatment is needed. These findings also support recent efforts to clinically characterize speech-in-noise deficits in listeners beyond the pure-tone audiograms (Musiek et al. 2017; Fitzgerald et al. 2024; Smith et al. 2024).

SUMMARY AND FUTURE DIRECTIONS

In summary, the study investigated the relationship between envelope fidelity and speech intelligibility in a pooled dataset from four methodologically similar studies using a Bayesian analysis framework. Results confirmed that speech intelligibility improved with higher envelope fidelity, even after compensating for loss of audibility. Working memory emerged as the primary source of individual variability in this relationship, after accounting for age and PTA. The pooled dataset provided a large sample size to detect these effects. These findings highlight the importance of considering individual cognitive abilities, as audibility alone may be insufficient for optimizing speech intelligibility outcomes with hearing aids.

The findings from this study suggest avenues for clinical application and future research. Clinically, the model may be useful to understand how individual variability can impact outcomes with specific hearing aid parameters. While not the primary question in this study, we examined this descriptively by interpreting observed effects from our model of frequency lowering (see Figure A in Supplemental Digital Content 2, https://links.lww.com/EANDH/B767). Next, while the model supports the idea that the envelope fidelity metric may be a useful tool to identify individuals who are susceptible to signal distortions, the envelope fidelity metric has been validated primarily under laboratory conditions. There is a need for metrics that can capture listener experience and hearing aid distortions in real-world environments and under clinical fitting conditions. A promising approach is to explore the use of these (or similar) acoustic metrics to triage individuals into different treatment paths. For example, some listeners may need specific signal processing adjustments, while others might benefit from alternative rehabilitative approaches, such as listening training. Furthermore, targeted counseling based on these metrics could help set realistic expectations for the patient in difficult listening conditions. In addition, while the present study used the RST as a measure of working memory, this test in its current form is not validated for clinical use. In future work, it may be helpful to consider individualized treatment in the context of other measures of working memory, such as the Repeat Recall Test (Kuk et al. 2024; Slugocki et al. 2025) and Word Auditory Recognition and Recall Measure (Smith et al. 2016, 2020) that are being developed for clinical use. Such tools may assist in the goal of determining how the variability in cognition can be used to individualize treatment.

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Northwestern University Institutional Review Board provided consent for this research under protocol numbers STU00061167 (P.S.), STU00204188 (P.S.), and STU00210459 (V.R.).

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

The authors have no conflicts of interest to disclose.

Address for correspondence: Varsha Rallapalli, Department of Communication Sciences & Disorders, University of South Florida, 4202 E Fowler Avenue, PCD 1017, Tampa, FL 33620, USA. E-mail: vrallapalli@usf.edu

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