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Impact of Aging and the Electrode-to-Neural Interface on Temporal Processing Ability in Cochlear-Implant Users: Amplitude-Modulation Detection Thresholds

Maureen J. Shader, Sandra Gordon-Salant, and Matthew J. Goupell

Abstract

Although cochlear implants (CIs) are a viable treatment option for severe hearing loss in adults of any age, older adults may be at a disadvantage compared with younger adults. CIs deliver signals that contain limited spectral information, requiring CI users to attend to the temporal information within the signal to recognize speech. Older adults are susceptible to acquiring auditory temporal processing deficits, presenting a potential age-related limitation for recognizing speech signals delivered by CIs. The goal of this study was to measure auditory temporal processing ability via amplitude-modulation (AM) detection as a function of age in CI users. The contribution of the electrode-to-neural interface, in addition to age, was estimated using electrically evoked compound action potential (ECAP) amplitude growth functions. Within each participant, two electrodes were selected: one with the steepest ECAP slope and one with the shallowest ECAP slope, in order to represent electrodes with varied estimates of the electrode-to-neural interface. Single-electrode AM detection thresholds were measured using direct stimulation at these two electrode locations. Results revealed that AM detection ability significantly declined as a function of chronological age. ECAP slope did not significantly impact AM detection, but ECAP slope decreased (became shallower) with increasing age, suggesting that factors influencing the electrode-to-neural interface change with age. Results demonstrated a significant negative impact of chronological age on auditory temporal processing. The locus of the age-related limitation (peripheral vs. central origin), however, is difficult to evaluate because the peripheral influence (ECAPs) was correlated with the central factor (age).

Keywords

cochlear implant, aging, temporal processing, neural survival, AM detection

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Cochlear implants (CIs) deliver signals that are highly degraded in the spectral domain, requiring CI users to attend to the temporal properties of the signal to recognize speech. Despite this signal degradation, many CI users have excellent speech recognition abilities without the aid of visual cues (Gifford et al., 2008; Schvartz-Leyzac et al., 2019). However, there is a large amount of individual variability in speech recognition performance (Blamey et al., 2013; Holden et al., 2013), some of which can be explained by individuals' ability to accurately process temporal information. One population that is at risk for acquiring temporal processing deficits is older adults over 65 years of age (e.g., Fitzgibbons & Gordon-Salant, 1996).

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Chronological age in adult CI users has been identified as a predictor of speech recognition performance, with younger adults outperforming older adults on various speech recognition measures (Blamey et al., 2013; Chatelin et al., 2004; Friedland et al., 2010; Roberts et al., 2013; Sladen & Zappler, 2015). After accounting for the effect of duration of deafness, Blamey et al. (2013) found a significant negative effect of age at implantation for individuals over the age of 70 years. In a smaller scale study, Sladen and Zappler (2015) divided participants into two age groups that were matched for duration of deafness and found that the older group performed significantly worse than the younger group on speech recognition tasks in quiet and in noise. The presence of auditory temporal processing deficits in older CI users could contribute to the deleterious effect of age on speech recognition performance.

Temporal processing ability generally refers to an individual's ability to detect or to discriminate between subtle changes in a signal that occur in the time domain. One commonly used assessment of temporal processing is amplitude-modulation (AM) detection. AM signals are dynamic and are similar to AM fluctuations that are present in the speech envelope. Age-related declines in temporal envelope processing have been observed in animal models (Walton et al., 2002) and in humans (Grose et al., 2009; He et al., 2008; Leigh-Paffenroth & Fowler, 2006; Purcell et al., 2004), suggesting a general decline in the synchronization of neural responses to temporal envelope fluctuations with advancing age. Temporal acuity, as it relates to the rate that neural units are able to phase lock to electrical pulse trains, also decreases after long periods of deafness (Middlebrooks, 2018). Prolonged periods of auditory deprivation can be more likely to occur in older CI users. Despite the evidence for age-related declines in temporal envelope processing, the impact of age on AM detection ability has not been evaluated in CI users. It is reasonable to hypothesize that age-related declines in temporal processing may put older CI users at a disadvantage for perceiving speech via a CI.

AM detection ability in CI users varies as a function of signal-related factors, including presentation level, electrical stimulation/carrier rate, and electrode location. Generally, AM detection ability tends to worsen with decreasing presentation level (Galvin & Fu, 2005; Pfingst et al., 2007), increasing carrier rate (Galvin & Fu, 2005, 2009; Pfingst et al., 2007), and decreasing electrical dynamic ranges (DRs; Pfingst et al., 2007). The magnitude of these effects varies greatly between listeners, suggesting that listener-related factors including biological variables may impact performance.

AM detection thresholds have been shown to vary across different electrode locations within a single CI user (Garadat et al., 2012; Pfingst et al., 2007). Cochlear pathology, and the resulting survival of spiral ganglion cells (SGCs), are highly variable along the length of the cochlea as well as between individuals (Hinojosa & Marion, 1983; Khan et al., 2005). Differences in the neural survival pattern at each electrode location may underlie these across-electrode differences in AM detection thresholds. One measurement that is used to estimate SGC density in CI users is the amplitude growth function (AGF) of the electrically evoked compound action potential (ECAP), which is a representation of the input–output function of the ECAP peak-to-peak amplitude response with increasing current level (Schvartz-Leyzac & Pfingst, 2018). Steeper ECAP AGFs (or steeper growth functions of wave I of the auditory brainstem response) have been shown to be indicative of better peripheral neural survival in multiple animal models (Hall, 1990; Pfingst et al., 2017; Ramekers et al., 2014; Smith & Simmons, 1983). It is important to note, however, that the slope of the ECAP AGF can reflect a combination of neural and nonneural factors, including the distance from the electrode to the modiolus, electrode impedances, and electrode orientation (Grill et al., 2009; Miller et al., 1993; Van de Heyning et al., 2016). While many of these factors can be accounted for in animal studies, experiments in human CI users cannot rule out the contribution of nonneural factors to the slope of the ECAP growth function.

Although AM detection has been studied extensively in CI users (e.g., Chatterjee & Oba, 2005; Chatterjee & Oberzut, 2011; Chatterjee & Robert, 2001; Fraser & McKay, 2012; Galvin & Fu, 2005) and has been shown to correlate with speech recognition ability (Cazals et al., 1994; Fu, 2002; Garadat et al., 2012), very little research has focused on the impact of listener-related factors on AM detection in CI users. Previous psychophysical studies with CIs users also tend to have relatively small sample sizes and limited consideration of participants' chronological age, age at onset of hearing loss, and estimation of the degree of neural survival. In addition, many previous studies only measured AM detection on a single electrode for each participant. The choice of electrode could confound the results due to differences in neural survival across the electrode array. It is possible that these differences may underlie some of the individual variability observed in CI users.

The number of SGCs declines for increasing durations of deafness (Leake et al., 1999) as well as advancing age (Makary et al., 2011; Sergeyenko et al., 2013). In addition, altered temporal discharge patterns are observed in electrically stimulated SGCs that have experienced prolonged periods of auditory deprivation (Shepherd & Javel, 1997). Therefore, reduced neural survival due to aging may effectively reduce CI users' temporal processing as measured on an AM detection task.

A reduction in temporal envelope processing has important implications for CI users because they must rely primarily on temporal envelope modulations to understand speech. These consequences of reduced temporal processing could be an underlying source of older CI users' speech recognition limitations.

Because auditory temporal processing ability declines with increasing age, even in the absence of hearing loss (CHABA, 1988), psychophysical temporal processing tasks are often considered measures of *central* auditory processing (e.g., Fitzgibbons & Gordon-Salant, 1995). It is, however, difficult to estimate the independent contribution of the central auditory system that is free from influences from the peripheral auditory system (Humes et al., 2012). CIs bypass many cochlear structures and stimulate the SGCs directly, which makes CI users a novel population in which to measure the role of the central auditory system on temporal processing ability without much of the confounding influence of the peripheral auditory system. The only remaining peripheral contribution in CI users is the electrode-to-neural interface or the quality of the transmission of electrical stimulation to the intended SGCs. The electrode-to-neural interface can refer to the many factors that can either prevent or facilitate the transmission of electrical signals from an intracochlear electrode to the adjacent neural population. At the level of the electrode, factors that can affect the electrode-to-neural interface include the distance from the electrode to the modiolus (Saunders et al., 2002), electrode configuration (Bierer & Faulkner, 2010), and the impedance values for both the stimulating and recording electrode (Grill et al., 2009). At the neural level, the number of surviving SGCs (e.g., SGC density; Hinojosa & Marion, 1983) and the health of those SGCs (Pfingst et al., 2015) can directly impact the quality of the electrode-to-neural interface. A poor electrode-to-neural interface is associated with smaller electrical DRs and steeper loudness growth functions, which may diminish performance with a CI (Bierer & Nye, 2014). Therefore, to estimate the independent contribution of the central auditory system to temporal processing ability in CI users, the contribution of the degree of peripheral neural survival was also estimated.

The goal of this study was to identify the effect of age among CI users on AM detection ability at different electrical carrier rates. The contribution of other age-related factors (peripheral neural survival estimates) to participants' performance on the AM detection task was also assessed. Based on the results from studies that tested younger and older normal-hearing listeners, it was hypothesized that older CI users would require larger depths of modulation compared with younger CI users and middle-aged CI users to detect the presence of AM in electrical pulse trains because of age-related auditory temporal processing limitations. Furthermore, it was hypothesized that the age effects would be larger for stimuli presented at relatively fast electrical carrier rates because of the altered temporal discharge patterns associated with age-related SGC degeneration. It was also hypothesized that older CI participants would have relatively shallow ECAP AGF slopes compared with younger and middle-aged CI participants due to age-related reductions in SGCs.

Method

Participants

Twenty-two participants were recruited to represent a wide range of ages from 23 to 84 years (mean = 56.1 ± 18 years) with at least two participants' ages falling into each decade. All participants passed a cognitive screening for dementia with a score of ≥22 on the Montreal Cognitive Assessment (Nasreddine et al., 2005). A Montreal Cognitive Assessment score of 22 to 25 indicates that an individual is at risk for mild cognitive impairment (Cecato et al., 2016). These individuals were not excluded from participating in the experiment, which is consistent with the recommendations by Dupuis et al. (2015) for individuals with hearing impairment. Moreover, age is of primary importance in this study and the practice of excluding older participants who were considered "at risk" of cognitive impairment would significantly limit the recruiting potential for older participants. All participants were implanted with Cochlear-brand devices. Participant demographics are provided in Table 1. All participants were required to have at least 6 months of CI experience.

Mapping

Each participant's electrical DR was measured by establishing threshold ("T") and maximum comfortable ("M") levels using standard CI mapping procedures for each test electrode for every carrier rate. T levels were defined as the smallest amount of electrical current needed to detect a 500-ms constant-amplitude pulse train 100% of the time. M levels were defined as the upper limit of a participant's comfortable volume range. Electrical DR was calculated as the current range from T level to M level for each electrode. Direct stimulation best practices were followed to perform these experiments (Litovsky et al., 2017).

Stimuli and Procedure

All stimulus presentation was performed using direct stimulation of the electrode array with the Nucleus Implant Communicator (NIC2) and an L34 research sound processor. Stimuli were 500-ms AM electrical

Table 1. Participant Demographics.

Participant	Age	Gender	Age at HL onset	Duration of HL	Etiology	Device	MoCA score
S1	23	M	0	12	Connexin 26	CI24RE(CA)	27
S2	25	M	4	14	Hereditary	CI24RE(CA)	27
S3	27	F	0	20	Connexin 26	CI512(CA)	29
S4	30	M	10	9	Hereditary	CI24RE(CA)	27
S5	37	F	5	15	Hereditary	CI24M	30
S6	41	M	1	37	Meningitis	CI422	28
S7	45	M	26	5	Cogan syndrome	CI24R(CS)	22
S8	50	F	38	1	Hereditary	CI24RE(CA)	29
S9	50	F	3	44	Unknown	CI24RE(CA)	27
S10	54	F	41	3	Hereditary	CI24RE(CA)	27
S11	54	F	40	7	Endocarditis	CI512(CA)	24
S12	59	M	5	47	Hereditary	CI24RE(CA)	26
S13	64	F	4	53	Rh incompatibility	CI512(CA)	30
S14	65	F	0	57	Unknown	CI24RE(CA)	27
S15	65	F	0	47	Unknown	CI24M	CNT
S16	69	F	2	60	Measles	CI24RE(CA)	29
S17	71	F	5	49	Unknown	CI24RE(CA)	28
S18	75	F	50	20	Unknown	CI24RE(CA)	26
S19	76	M	70	1	Ototoxicity	CI512(CA)	28
S20	81	F	35	41	Unknown	CI24RE(CA)	27
S21	83	M	77	2	Aging	CI24RE(CA)	28
S22	84	M	62	12	Noise induced	CI24RE(CA)	26

Note. HL = hearing loss; duration of HL = number of years that hearing loss of any degree was experienced prior to implantation; MoCA = Montreal Cognitive Assessment; CNT = could not test due to severe vision loss; M = male; F = female. Participant S15 was able to complete the auditory portions of the MoCA that did not require vision without difficulty and was included the study.

biphasic pulse trains, and each pulse had a 25-µs phase duration and an 8-µs interphase gap. Monopolar stimulation was used. Stimuli had AM applied using seven modulation depths (1%, 3%, 5%, 10%, 25%, 50%, and 100% of the DR) and three modulation frequencies (50, 100, and 250 Hz). Two carrier rates (500 and 4000 pulses per second [pps]) were used to convey the AM.

ECAP Amplitude Growth Functions. ECAP AGFs were measured at five electrode locations (electrodes 4, 8, 12, 16, and 20) using Custom Sound EP software provided by Cochlear Ltd. ECAPs were collected using the forward-masking subtraction procedure (Abbas et al., 1999; Brown et al., 1990) with an 80-pps probe rate, 50-µs phase duration, and a 7-µs interphase gap. The recording electrode was selected to be two electrodes away from the measurement electrode in the basal direction. The masker pulse had the same stimulation parameters as the probe pulse with a +10 current unit (CU) offset in input level (the masker pulse was 10 CUs higher than the probe pulse). ECAP stimulation parameters were the same for all electrode locations and all participants. Measurements were collected at an initial presentation level below a participant's threshold level and increased in 5 CU steps up to a maximum comfort level. Participants were instructed to indicate when the ECAP stimuli reached a level at which any further increase would cause the stimulus to be uncomfortable. A linear ECAP slope was computed by transforming the input values from the logarithmic CU scale to a linear charge scale (nC). Linear input values in nC were used to calculate the slope of the linear input–output function for each electrode. The slope was derived in a similar approach as described by Schvartz-Leyzac and Pfingst (2018). Slope values were calculated by determining a best-fit line that included all monotonically increasing data points (ECAP peak-to-peak amplitudes) with increasing input values. For electrodes that showed non-monotonic patterns of responses at high input levels, the slope was calculated only including data points along the growth function that produced an increase in peak-to-peak amplitude relative to the previous data point measured at a lower input level. Based on the sample of ECAP AGFs from the five electrode locations across the array, two electrodes were selected for the AM detection procedure. The electrode with the steepest AGF was selected as the participant's "steep" electrode location, while the electrode with the shallowest AGF was selected as the participant's "shallow" electrode location. In this way, AM detection was evaluated at an electrode location with a relatively good and a relatively poor electrode-to-neural interface in terms of ECAP amplitude growth. In 2 of the 22 participants, ECAPs could not be recorded from one or more electrodes from the subset of five electrodes selected (electrodes 4, 8, 12, 16, and 20). In those cases, the two test electrodes were selected from the reduced subset of electrodes that had ECAP responses.

Loudness Balancing. Loudness cues were limited using techniques similar to those suggested by Fraser and McKay (2012). Loudness balancing was performed using a loudness matching procedure for each AM depth, modulation frequency, and carrier rate, at each electrode. Loudness-balanced levels were used for stimulus presentation to remove potential loudness cues that may signal the presence of AM. In addition, a ± 4 CU level roving was applied to each stimulus interval to further obscure loudness cues (Fraser & McKay, 2012).

In the loudness-matching procedure, the reference stimulus consisted of an unmodulated pulse train presented at 80% of the DR (e.g., Fu, 2002). A percentage of the DR was chosen as the initial presentation level to control for differences in loudness growth functions across the electrode array that may disrupt the effective AM depth represented at each electrode location. This reference stimulus was compared with an AM target stimulus. Each target AM signal (for every modulation depth, at each modulation frequency, carrier rate, and test electrode) was presented between two of the unmodulated reference signals. Participants were instructed to report whether the target signal needed to be increased or decreased in volume in order to be equal to the two unmodulated reference signals. The current level of the target signal was adjusted in 1-CU steps until the participant reported that all three signals were equal in volume. The loudness-balanced level was recorded for each target AM signal. This procedure was repeated a minimum of 3 times. The average current level of the volume-adjusted AM signals across all three trials was set as the final loudness-balanced stimulus. This procedure was repeated for each condition for two test electrodes.

AM Detection. AM detection thresholds (i.e., modulation detection thresholds [MDTs]) were measured for two electrodes ([1] electrode with the steepest ECAP slope and [2] electrode with the shallowest ECAP slope). MDTs were collected using a three-interval, two-alternative forced-choice task with an interstimulus interval of 500 ms. MDTs were established for AM frequencies of 50, 100, and 250 Hz using a method of constant stimuli, which obtained psychometric functions for each AM-rate condition plotted as percentage correct detection as a function of modulation depth. Final psychometric functions were constructed based on average percent correct detection of AM stimuli over 50 trials as a function of modulation depth for each AM rate and for each carrier rate. Participants were instructed to select the "different" sound that may differ in sound quality, timbre, or pitch. No feedback was provided. The presentation of stimuli was blocked within each carrier rate condition; the order of the electrodes tested in each rate block was randomized. The order of the conditions and electrodes tested was randomized across participants.

Statistical Analyses

A three-level generalized linear (logistic) mixed-effects model (GLMM) was used to fit participants' AM detection performance functions. This was done using the R Studio software interface with the lme4 package (Bates et al., 2014) and following the model building recommendations from Hox et al. (2017). An intercept-only model was constructed as a first step and was used as a benchmark. Second, all main effects and interactions between Level 1 predictor variables were added to the fixed effects structure: carrier rate (two levels: "0" = 500 pps [reference level], "1" = 4000 pps), modulation frequency (three levels: "−2" = 50 Hz, "−1" = 100 Hz, "0" = 250 Hz [reference level]), and modulation depth (three levels: "0" = 1% and 3% [reference level], "1" = 5% and 10%, "2" = 25%, 50%, and 100%). During experimental testing, the modulation depths included seven fixed levels. For analysis purposes, however, data for similar depths were combined to represent small (1% and 3%), moderate (5% and 10%), and large (25%, 50%, and 100%) modulation depths in order to make more interpretable comparisons between modulation depth and other Level 1 and (potentially) Level 2 variables. Nonsignificant interactions that did not result in any improvement in model fit (evaluated with a χ^2 significance test) were removed from the model at this step.

Next, the main effects and interactions for all Level 2 predictors (age, age at onset of deafness, duration of hearing loss, and ECAP slope) were added to the fixed effects. Values for all Level 2 predictors were standardized (z scores) before being entered into the model. As a result, all Level 2 coefficients that remained in the model represented changes to AM detection with increasing or decreasing that particular variable on a standard deviation (SD) scale. Standardized ECAP slopes were designated as either the "steep" or "shallow" electrode by a nested variable in the random effects structure.

The three-level model was reflected in the random effects structure in which two electrode locations ("0" = steep ECAP [reference level], "1" = shallow ECAP) were nested within subject. Because each subject was tested at two electrode locations, measurements at the electrode level are not independent of one another. In this way, standardized ECAP slope values (classified as a continuous numeric variable) could be added to the model as a Level 2 predictor variable because slopes were recognized as an attribute of its respective electrode within its respective subject.

Finally, random slope variation for each Level 1 predictor was added to the model on a variable-by-variable basis to avoid an overparameterized model. All predictors that had significant variance across subjects and resulted in model convergence remained in the model. Cross-level interactions between Level 2 and Level 1 (only Level 1 predictors that had significant random variance across subjects) were added to the fixed effects.

Results

Effects of Modulation Depth, Modulation Frequency, and Carrier Rate

The results of the GLMM are shown in Table 2. Results revealed significant main effects of modulation depth, modulation frequency, and carrier rate on the detection of AM. As the modulation depth increased, the likelihood of detecting AM increased. At moderate depths of 5% to 10% modulation, participants were 2.17 times more likely to detect AM compared with small depths of 1% to 3% ($p < .001$). Participants were 3.97 times more likely to detect AM at large modulation depths of 25% to 100% compared with small depths ($p < .001$). As the modulation frequency decreased, the likelihood of AM detection increased. Compared to the highest modulation frequency of 250 Hz, participants were 1.75 times more likely to detect AM at 100 Hz ($p < .001$). At 50 Hz, participants were 1.69 times more likely to detect AM compared with 250 Hz ($p < .001$). This result reflects the low-pass characteristics of the auditory system for identifying the presence of modulated signals. There was also a main effect of carrier rate. As carrier rate increased from 500 pps to 4000 pps, participants were less likely (0.75 times) to detect AM ($p = .009$).

Significant two-way interactions were identified between the depth of modulation and the modulation frequency. These four interactions, including Moderate

Table 2. Final GLMM for AM Detection.

Fixed Effects	Coefficient	SE	Z	*p*	Odds Ratio
Intercept	**0.602**	**0.217**	**2.773**	**0.005**	1.83
Modulation Depth: Small (1–3%; ref)					
Moderate (5–10%)	**0.774**	**0.059**	**13.026**	**<0.001**	2.17
Large (25–100%)	**1.380**	**0.060**	**22.981**	**<0.001**	3.97
Modulation Freq: 250 Hz (ref)					
50 Hz	**0.526**	**0.055**	**9.632**	**<0.001**	1.69
100 Hz	**0.557**	**0.055**	**10.178**	**<0.001**	1.75
Carrier Rate: 500 pps (ref)					
4000 pps	**−0.291**	**0.112**	**−2.589**	**0.009**	0.75
Age (standardized)	**−0.791**	**0.206**	**−3.845**	**<0.001**	0.45
Interactions					
Moderate Depth × 50 Hz	**0.787**	**0.094**	**8.400**	**<0.001**	2.20
Large Depth × 50 Hz	**1.685**	**0.156**	**10.833**	**<0.001**	5.39
Moderate Depth × 100 Hz	**0.736**	**0.094**	**7.867**	**<0.001**	2.09
Large Depth × 100 Hz	**1.168**	**0.131**	**8.926**	**<0.001**	3.22
Moderate Depth × 4000 pps	−0.085	0.081	−1.050	0.294	0.92
Large Depth × 4000 pps	**0.409**	**0.085**	**4.814**	**<0.001**	1.50
50 Hz × 4000 pps	**0.326**	**0.077**	**4.250**	**<0.001**	1.38
100 Hz × 4000 pps	**0.314**	**0.077**	**4.074**	**<0.001**	1.37
Moderate Depth × 50 Hz × 4000 pps	−0.105	0.127	−0.822	0.411	0.90
Large Depth × 50 Hz × 4000 pps	0.411	0.263	1.567	0.117	1.51
Moderate Depth × 100 Hz × 4000 pps	**−0.471**	**0.125**	**−3.772**	**<0.001**	0.62
Large Depth × 100 Hz × 4000 pps	−0.087	0.190	−0.459	0.646	0.92

Random Effects	**Variance**	**SD**
Subject Intercept	0.844	0.918
Subject Rate Slope	0.110	0.332
Electrode within Subject Intercept	0.261	0.511
Electrode within Subject Rate Slope	0.148	0.385

Note. SE = standard error; SD = standard deviation; Bold text indicates significance at the $p < .05$ level.

Depth × 50 Hz, Large Depth × 50 Hz, Moderate Depth × 100 Hz, and Large Depth × 100 Hz, relate to AM performance in these conditions compared with AM detection at the reference condition (Small Depth × 250 Hz). The reference condition characterizes the most difficult condition under which to detect AM. These two-way interactions suggest an exponential improvement in AM detection performance for increasing depths of modulation at lower modulation frequencies, but a more linear increase in performance at the higher modulation frequency of 250 Hz. Figure 1 shows the mean AM detection performance functions for each experimental condition and highlights the interactions between modulation depth and modulation frequency, as well as the interactions with carrier rate.

There was a significant two-way interaction of Large Depths × 4000 pps. This result suggests that the negative effect of 4000 pps on AM detection ability is overcome for greater, more salient, depths of modulation. Similarly, two-way interactions between modulation frequency and carrier rate (50 Hz × 4000 pps and 100 Hz × 4000 pps) suggest that AM detection at slower modulation frequencies was not negatively impacted by the faster carrier rate to the same degree compared with 250 Hz. Finally, there was also a significant three-way interaction of Moderate Depths × 100 Hz × 4000 pps. This finding suggests that although the negative effect of increasing the carrier rate was mitigated for larger modulation depths and for lower modulation frequencies, a participant was less likely to detect AM of moderate depths at 100 Hz at 4000 pps compared with the detection of small depths at 250 Hz at 500 pps (the reference condition). To summarize, this result suggests that the negative effect of increasing the carrier rate on AM detection persists for moderate depths at 100 Hz.

Effect of Chronological Age on AM Detection

The final model revealed a significant main effect of chronological age ($p < .001$), suggesting that with every 1 *SD* increase in age (representing an interval of 18 years), a participant was 0.45 times less likely to detect AM. There were no significant cross-level interactions between age and any Level 1 predictors. No other subject-level factors (e.g., age at onset of hearing loss, duration of hearing loss, or ECAP slope) were significant. This finding suggested that electrodes with the steepest ECAP slope did not exhibit significantly better MDTs compared with electrodes with the shallowest ECAP slope. Figure 2 displays the probability of AM detection when participants were divided into three age groups: younger (age: ≤38 years [$SD < -1$]), middle-aged (age: 39–73 years [$-1 < SD < 1$]), and older (age: ≥74 years [$SD \geq 1$]). Overall, the younger group correctly detected the presence of AM 87% of the time, the middle-aged group detected AM 78% of the time, and the older group detected AM 70% of the time.

MDTs were also calculated from each participant's psychometric performance function. MDT was defined as the interpolated AM depth that was correctly detected 70.7% of the time when the psychometric function was fit with a sigmoidal function. MDT was then converted to dB re: 100% modulation depth (20log[m]). The final temporal modulation transfer functions are plotted as MDTs as a function of AM frequency for each carrier

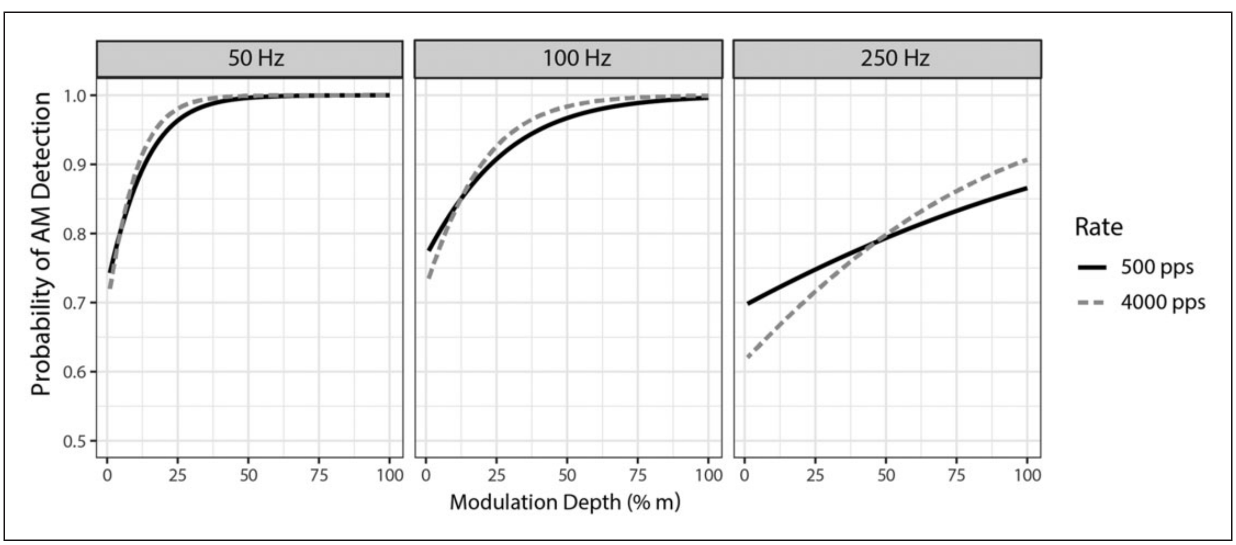

Figure 1. Mean Performance Functions for Detecting AM at Each Modulation Frequency and for Each Carrier Rate. AM = amplitude modulation.

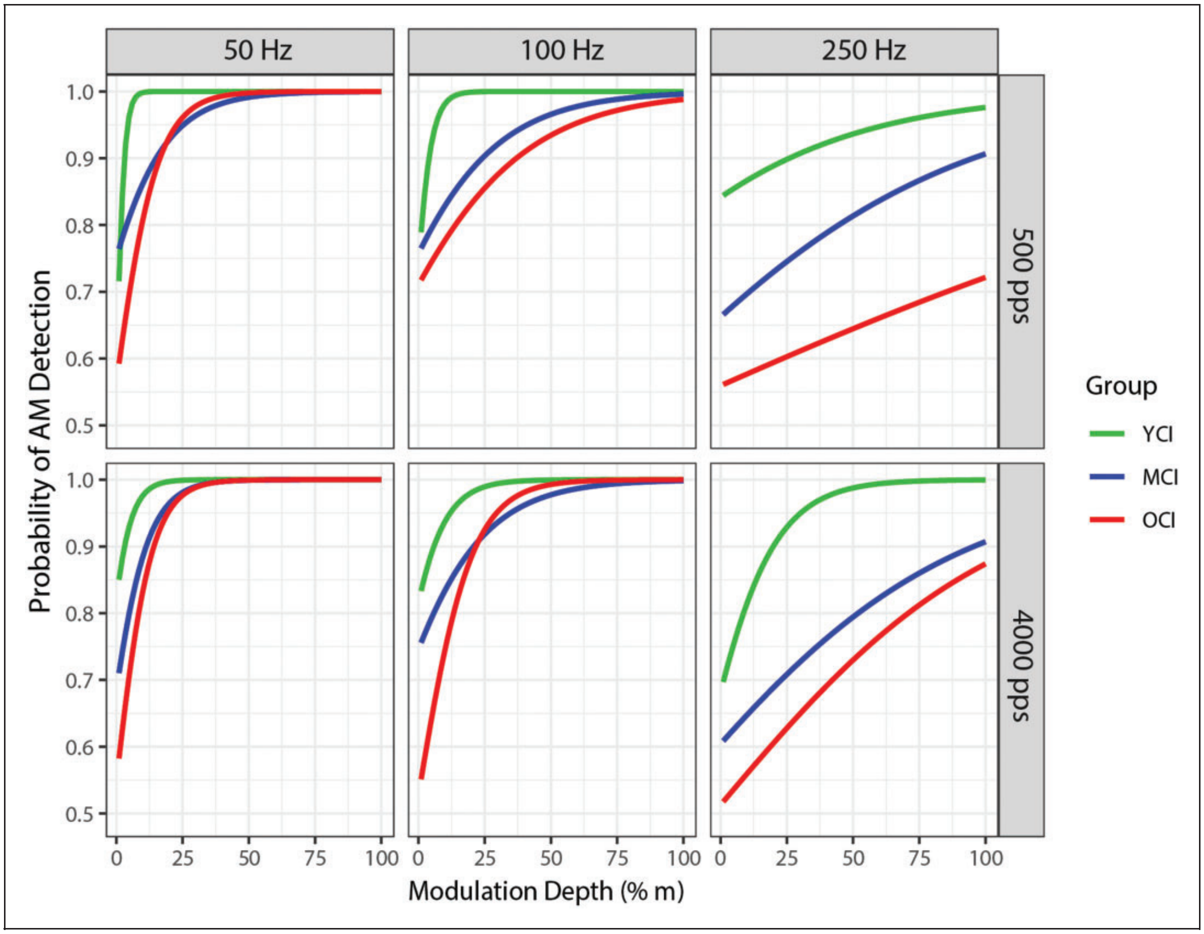

Figure 2. Mean Performance Functions for Detecting AM in Each Experimental Condition Separated by Age-Group. Green lines show performance for "younger" (YCI) participants $\leq$38 years of age ($N = 6$; age values $= SD \leq -1$]). Blue lines show "middle-aged" (MCI) participants between 39 and 73 years of age ($N = 10$; age values $= -1 < SD < +1$). Red lines show "older" (OCI) participants $\geq$74 years of age ($N = 6$; age values $= SD \geq +1$). AM = amplitude modulation.

rate in Figure 3. Overall, the results show an expected pattern of poorer AM detection with increasing modulation frequency. The main effect of age is clearly highlighted in Figure 3, which shows poorer MDTs with increasing age. MDTs were also related to the DR of the electrode; larger DRs were associated with better (lower) MDTs. Pearson correlations (with Bonferroni corrections) revealed significant relationships between DR and MDTs for both electrode locations using 500 pps: "steep" electrodes ($r = -.734$, $p < .01$) and "shallow" electrodes ($r = -.661$, $p < .01$) and using 4000 pps: "steep" electrodes ($r = -.618$, $p < .01$) and "shallow" electrodes ($r = -.590$, $p < .01$).

ECAP slopes, including both sets of "steep" and "shallow" electrodes, are plotted as a function of age in Figure 4. There were significant negative correlations between ECAP slopes and chronological age for both electrode locations: "steep" electrodes ($r = -.624$, $p < .01$) and "shallow" electrodes ($r = -.638$, $p < .01$). These correlations suggested that estimated peripheral neural survival declined with age in this group of CI users.

Discussion

Signal-Related Factors: Modulation Depth, Modulation Frequency, and Carrier Rate

This study investigated the relative contributions of signal-related factors (including electrical carrier rate, modulation frequency, and modulation depth) and listener-related factors (including chronological age, age at onset of hearing loss, duration of hearing loss, and the electrode-to-neural interface [as estimated by ECAP AGF slope]) to AM detection ability in adult CI users. AM detection was measured for seven depths of modulation, which were divided into three categories for statistical analysis: small (1% and 3%), moderate (5% and 10%), and large depths (25%, 50%, and 100%).

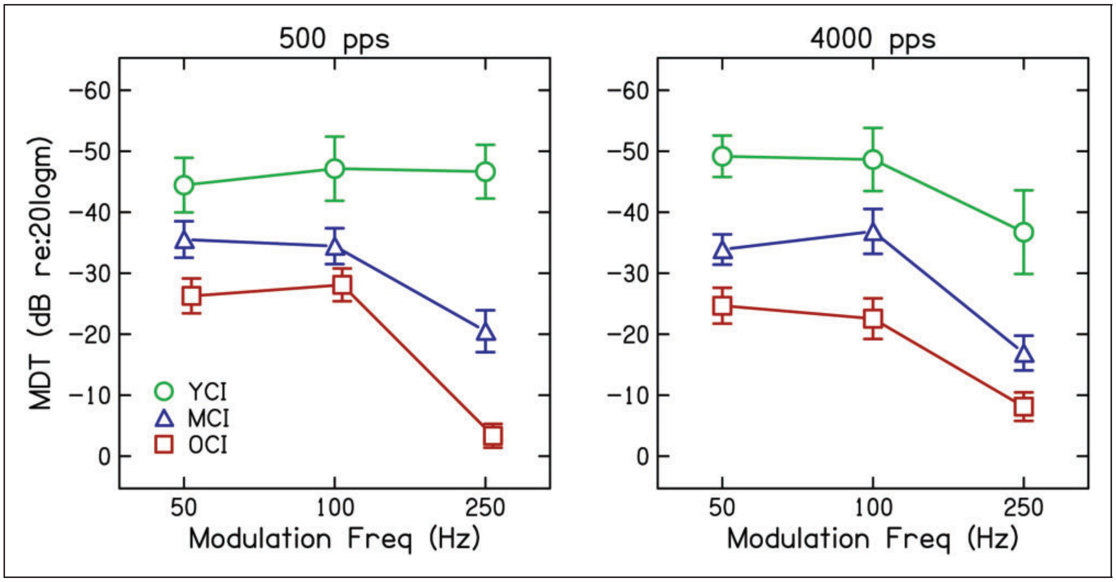

Figure 3. Temporal Modulation Transfer Functions (MDTs Plotted as a Function of Modulation Frequency) for Each Age-Group for the 500-pps Carrier Rate Condition (Left Panel) and the 4000-pps Carrier Rate Condition (Right Panel). YCI group ($N = 6$, age < 38 years). MCI group ($N = 10$, age = 38–73 years). OCI group ($N = 6$, age > 73 years). Data points represent average group MDTs for both electrode locations for each modulation frequency condition. Error bars represent ±1 standard error. MDT = modulation detection threshold; YCI = younger CI; MCI = middle-aged CI; OCI = older CI.

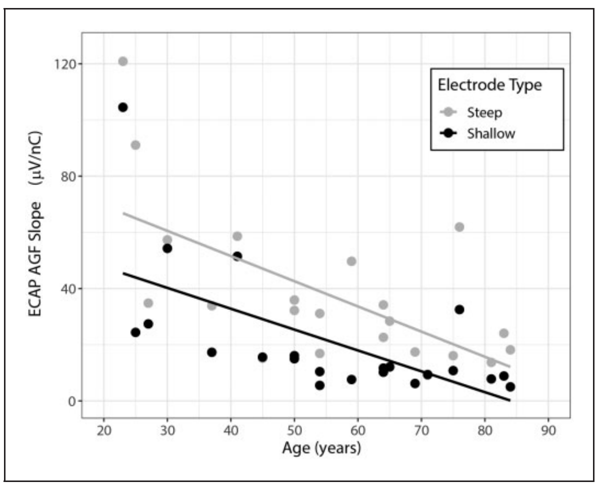

Figure 4. ECAP AGF Slopes Plotted as a Function of Age. Gray symbols represent slopes obtained from participants' "steep" electrodes. Black symbols represent slopes from participants' "shallow" electrodes. ECAP = electrically evoked compound action potential; AGF = amplitude growth function.

Figure 1 shows that the probability of accurate AM detection increased with increasing the modulation depth in every condition. AM detection also varied as a function of modulation frequency, with higher modulation frequencies resulting in poorer performance. Significant interactions between modulation depth and modulation frequency suggested that participants were more likely to detect AM in every experimental condition when compared with the reference condition. The reference condition, which compared performance at a small depth, 250-Hz modulation frequency, and 500-pps carrier rate to all other conditions, was the most difficult condition and was selected in order to capture the most variability between individual participants. This strategy provided the best chance for a three-level, mixed-effects model to account for significant variability at a subject level.

AM detection results showed a small decrease in performance using a 4000-pps carrier rate compared with a 500-pps carrier rate (Figure 1). Across all participants and all other stimulation parameters, AM was accurately detected 79% of the time at 500 pps and 77% of the time at 4000 pps, suggesting that participants were 0.75 times less likely to detect AM at a faster carrier rate. Previous studies have also shown a decrease in AM detection performance with increasing the electrical carrier rate (Galvin & Fu, 2005; Pfingst et al., 2007). Increases in the electrical stimulation/carrier rate produce CI maps with larger electrical DRs, which theoretically could provide more salient AM cues (e.g., more accurately represented at the neural level because of a larger range of amplitudes) compared with a small DR. In this study, larger DRs resulted in better MDTs regardless of the carrier rate being used. This result is consistent with other studies that also found a significant correlation between DR and MDTs, suggesting that larger DRs are associated with better MDTs (e.g., Pfingst et al., 2007). The benefit from lower carrier rates for increasing listeners' sensitivity to AM could be due to the relative difference in amplitude between consecutive pulses within a modulated pulse train. This idea, known as the "step-size hypothesis" proposed by Middlebrooks (2008), suggests better modulation detection and better neural phase-locking ability when the amplitude difference between successive pulses is large, which is the case for relatively low carrier rates. For higher carrier rates, both the amplitude step size and the timing between successive pulses are much smaller as compared with lower carrier rates.

There were significant interactions between modulation frequency and carrier rate (Figure 1). This finding demonstrated that even though performance was poorer overall for 4000 compared with 500 pps, the carrier rate effect was offset by increasing depths of modulation. Finally, a three-way interaction between Moderate Depth × 100-Hz Modulation Frequency × 4000-pps carrier rate suggested that the negative effect of a higher carrier rate persisted for only moderate depths of modulation at 100 Hz. To summarize, the rate effects were small enough to be essentially overcome by stronger predictor variables of AM detection, including modulation depth and modulation frequency.

Listener-Related Factors: Chronological Age and ECAP Slope

Results supported the hypothesis that older CI users require larger depths of modulation compared with younger users to detect the present of AM in electrical pulse trains (Figures 2 and 3) presumably because of age-related auditory temporal processing limitations. On average, younger participants were able to detect AM 87% of the time across all experimental conditions, while middle-aged participants detected AM 78% of the time, and older participants detected AM 70% of the time. Clinical CI sound processors produce amplitude modulations ranging between 10% and 40% modulation (Lindenbeck et al., 2020), but the actual modulation depths experienced by the CI user in everyday communication environments may be even smaller due to background noise and reverberation (Sayles & Winter, 2008). Thus, the age differences in AM detection ability in this study were observed within the range of typical modulation depths produced by a clinical CI processor and could have negative implications for older CI users.

It was also hypothesized that the age differences would be largest for the faster carrier rate conditions, due to altered temporal discharge patterns associated with age-related SGC degeneration. The results did not support this prediction as the final GLMM showed only a significant main effect of age, and no significant cross-level interactions involving age. This result may suggest that the major factor contributing to decreased AM detection ability in older participants is likely central in nature, rather than peripheral. Alternatively, it is possible that the size of the rate effect was too small to significantly vary between age groups. In addition, there were no significant effects of any other listener-related variables (i.e., age at onset of hearing loss, duration of hearing loss, or ECAP AGF slope). This result is somewhat contradictory to previous studies that investigated the relationship between AM detection ability and estimates of peripheral neural survival (Tejani et al., 2017).

Tejani et al. (2017) conducted a study that correlated psychophysical measures of AM detection and electrophysiological measures (ECAP) to AM pulse trains. Significant correlations were identified between behavioral MDTs and a modulated response amplitude of the ECAP responses (the difference in the maximum and minimum ECAP amplitude over the course of one full modulation cycle) for modulation frequencies below 1000 Hz. In other words, robust ECAP recordings were collected for all modulation frequencies, but AM detection ability decreased with increasing modulation frequency. This finding suggested a central limitation for AM encoding at higher modulation frequencies. One major difference between Tejani et al. and this study is the methodology in collecting and interpreting the ECAP response. This study collected ECAP AGFs in response to a single probe pulse. Tejani et al. collected multiple ECAPs, one for each pulse in a full modulation cycle. In addition, this study recruited 22 participants to represent a wide range of ages while the Tejani et al. study recruited eight CI users, seven of whom were between the ages of 54 to 77 years, with the remaining participant being a 39-year-old. Thus, a powerful examination of chronological age as it related to ECAP responses and to MDTs was not possible in that study.

Garadat et al. (2012) measured MDTs at all electrode locations in 12 adult CI users between the ages of 51 to 75 years. Modulation detection ability varied substantially across participants. Within a single participant, across-site AM detection from different electrode locations also varied significantly for many participants with no consistent pattern in this variation across participants. These findings suggested that AM detection performance was related to participant-specific irregularities in the electrode-to-neural interface across the array. This study found similar results, in that some participants had relatively large differences in MDTs across the two different electrode locations, while others did not. Garadat et al. did not evaluate the electrode-to-neural interface, so it is unknown whether or not those potential irregularities across a single electrode array could have accounted for any across-site differences in MDTs. However, in a subsequent study using the same group of participants, Garadat et al. (2013) created experimental CI programs for each participant in which the electrodes that were found to have the poorest MDTs were deactivated. When compared with their everyday programs, which had essentially all electrodes activated, participants exhibited improved scores for speech-in-noise and consonant discrimination measures when the poor MDT electrodes were deactivated, suggesting that poor AM detection ability was related to poor electrode-to-neural interfaces. The current study, however, did not find an effect of the electrode-to-neural interface as estimated by ECAP AGFs. It may be that ECAP slopes are not the most sensitive measure in which to examine specific aspects of the electrode-to-neural interface that impact AM detection. For example, recent evidence suggests that the relative differences in slope between ECAP AGF measurements that utilized different stimulation parameters (i.e., interphase gap duration) are predictive of speech recognition performance (Schvartz-Leyzac & Pfingst, 2018).

The results of this study support the hypothesis that older participants have shallower ECAP AGF slopes compared with younger participants, presumably because of age-related reductions in SGCs. However, ECAP slope was not a significant predictor of AM detection ability. One potential reason why ECAP slope did not significantly predict AM detection is because of the method of selecting only one "steep" and one "shallow" electrode based on the respective ECAP slope values. Another reason could be that the choice of a "steep" versus "shallow" electrode reflected a large difference in relative ECAP slope in some participants, but in others, only reflected a very small increase in slope. In other words, for some participants, the slope value for the "steep" electrode was substantially higher compared with all other electrodes (Figure 4). But in other participants, there were essentially little to no differences in slope values between the highest and lowest slopes. For example, one participant only had a 2 μV/nC difference in slope between electrodes, while another had a 66 μV/nC difference. Another potential reason why ECAP AGF slope did not significantly predict AM detection is because the ECAP slope could reflect the entire electrode-to-neural interface, not only the neural component. Other factors independent from neural survival can impact the slope of the ECAP AGF, including the distance from the electrode to the modiolus, electrode impedance, and the presence of fibrous tissue or bone growth. It cannot be ruled out that other factors besides neural survival could have contributed to the differences in ECAP AGF slope values across participants and across electrode locations within an individual participant. However, it could be argued that the most likely factor affecting age-related differences in the electrode-to-neural interface is a reduction of spiral ganglion density, rather than nonneural components (e.g., Makary et al., 2011).

Chronological age, rather than ECAP slope, was the sole listener-related factor that contributed to performance on this AM detection task. However, ECAP slope was correlated with age, with ECAP AGF slopes significantly decreasing with advancing age (Figure 4). It is important to note that the age at onset and etiology of deafness differed between younger and older participants, which may have contributed to the observed age effect. As a rule, younger participants tended to have an earlier onset of hearing loss and were more likely to have a genetic component to their deafness. A thorough investigation of factors of this nature would require a substantially larger sample of participants. Another approach would be to match younger and older participants for biological variables relating to their hearing histories in order to evaluate the effect of age alone. This strategy is also not readily feasible because of limitations in participant recruitment and availability. In addition, age was the only listener-related factor that significantly contributed to AM detection performance. However, Figure 4 shows that age and ECAP slope were closely related, with the majority of steeper ECAP slopes belonging to younger participants. It may be advantageous to match younger and older participants on the basis of internal electrode array and ECAP AGF slopes to investigate the contribution of peripheral factors separately.

In summary, these findings add considerable support to the notion that SGCs deteriorate with age. Even though CIs bypass cochlear structures that are influenced by aging in the peripheral auditory system, the number of surviving SGCs in the periphery still present a potential confound for delineating the effects of aging in the central auditory system from those in the peripheral auditory system. The age-related declines in auditory temporal processing for AM signals may be associated with changes to higher level central processes that occur beyond the level of the SGCs because performance on this task was not predicted by ECAP AGF slope. However, a peripheral contribution to the observed age limitation cannot be entirely ruled out as chronological age and ECAP AGF slope were correlated. Nevertheless, CIs present a unique model in which to examine aging effects in the auditory system.

Conclusions

This study investigated the effect of age and the electrode-to-neural interface on AM detection ability for multiple modulation depths and modulation frequencies at two electrical carrier rates. In general, AM detection improved with increasing the modulation depth. AM detection ability decreased with increasing the modulation frequency. AM detection also decreased slightly for the faster carrier rate compared with the slower rate. It was hypothesized that results would show an age-related decline in central temporal processing ability for detecting AM. It was also hypothesized that electrodes with poor electrode-to-neural interface estimates, presumably due to reduced peripheral neural survival (a reduction in SGCs), would have poorer AM detection ability compared with electrodes with good electrode-to-neural interface estimates. Results demonstrated that advancing age was associated with poorer AM detection performance overall. Peripheral status, as estimated by ECAP AGF slopes, declined with age but did not significantly contribute to AM detection ability. The apparent decline in peripheral neural survival estimates that accompanies aging limited the evaluation of the independent contributions from central aging per se and age-related changes in the peripheral system to auditory temporal processing ability for AM detection. Nevertheless, these results may explain some of the age-related deficits in speech recognition in CI users. A reduction in AM detection, or temporal envelope encoding in general, has important implications for CI users who must rely on temporal envelope modulations within the signal to understand speech. Natural speech is comprised of phonetic sounds at a wide range of amplitudes, with low-level components (i.e., consonants) being particularly important for accurate speech understanding. The results of this study suggest that older CI users, who show poorer AM detection ability compared with younger CI users, may benefit from sound processing strategies that increase the depth or saliency of amplitude modulations either for all input levels or primarily for low-level speech cues. Taken together, the findings indicate that older CI users exhibit age-related declines in temporal processing ability for an AM detection task. The age differences observed in this study could explain some of the individual variability observed in other studies that measured temporal processing in CI users.

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