ABSTRACT

Title of Dissertation: AUDITORY TEMPORAL PROCESSING ABILITY IN COCHLEAR-IMPLANT USERS: THE EFFECTS OF AGE AND PERIPHERAL NEURAL SURVIVAL

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Cochlear implants (CIs) are a valuable tool in the treatment of hearing loss and are considered a safe and effective option for adults of all ages. Nevertheless, older adults with CIs do not always achieve comparable speech recognition performance to younger adults following implantation. The mechanism(s) underlying this age limitation are unknown. It was hypothesized that older CI users would demonstrate age-related deficits in auditory temporal processing ability, which could contribute to an age limitation in CI performance. This is because the ability to accurately encode temporal information is critical to speech recognition through a CI. The current studies were aimed at identifying age-related limitations for processing temporal information using a variety of electrical stimulation parameters with the goal of identifying parameters that could mitigate the negative effects of age on CI performance. Studies 1 and 2 measured auditory temporal

processing ability for non-speech signals at the single-electrode level for various electrical stimulation rates. Specifically, Study 1 measured gap detection thresholds, which constitutes a simple, static measurement of temporal processing. Study 2 measured amplitude-modulation detection thresholds, which utilized relatively more complex and dynamic signals. Peripheral neural survival was estimated on each electrode location that was tested in Studies 1 and 2. Study 3 measured phoneme recognition ability for consonant contrasts that varied in discrete temporal cues at multiple stimulation rates and envelope modulation frequencies. Results demonstrated significant effects of age and/or peripheral neural survival on temporal processing ability in each study. However, age and the degree of neural survival were often strongly correlated, with older participants exhibiting poorer neural survival compared to younger participants. This result suggested that a substantial reduction in peripheral neural survival accompanies aging in older CI users, and that these factors should be considered together, rather than separately. Parametric variation in the stimulation settings impacted performance for some participants, but this effect was not consistent across participants, nor was it predicted by age or peripheral neural survival.

AUDITORY TEMPORAL PROCESSING ABILITY IN COCHLEAR-IMPLANT USERS: THE EFFECTS OF AGE AND PERIPHERAL NEURAL SURVIVAL

by

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Dedication

For my babies, Joey and Eddie. You are my sunshines.

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I would like to thank my teacher and mentor, Matt Goupell, for the countless hours he has dedicated to my training and professional growth. He has taught me more than I could ever acknowledge here. Thank you to my co-mentor, Sandy Gordon-Salant, for her guidance and advocacy, and for always keeping me on track. Although they did not always agree, Matt and Sandy have wanted nothing more than for me to succeed. I am immensely grateful to them for their many years of guidance and support.

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List of Abbreviations

AGC	Automatic gain control
AGF	Amplitude growth function
AM	Amplitude modulation
CI	Cochlear implant
CIS	Continuous interleaved sampling
CVC	Consonant-vowel-consonant
DoD	Duration of deafness
DR	Dynamic range
ECAP	Electrically evoked compound action potential
GDT	Gap detection threshold
GLMM	Generalized linear mixed-effects model
IPI	Inter-pulse interval
LME	Linear mixed-effects model
LPF	Low-pass filter
MCI	Middle-aged cochlear-implant users
MCL	Most comfortable level
MDT	Amplitude-modulation detection threshold
OCI	Older cochlear-implant users
SD	Standard deviation
SGC	Spiral ganglion cell
TMTF	Temporal modulation transfer function
VOT	Voice onset time
YCI	Younger cochlear-implant users

Introduction

Aging and Cochlear Implants.

A cochlear implant (CI) is an auditory prosthetic device that can partially restore the ability to hear for individuals with severe degrees of hearing loss. A CI has two main components: an internal device and an external sound processor. The internal device is composed of a receiver/stimulator and an electrode array, which is threaded through the mastoid and into the scala tympani of the cochlea. The electrode array bypasses damaged portions of the inner ear and directly stimulates the auditory nerve via electrical pulses originating from individual electrode contacts. Speech signal processing through a CI is characterized by a reduction in spectral resolution and temporal fine structure, while the temporal envelope remains relatively intact (Shannon, Zeng, Kamath, Wygonski, & Ekelid, 1995). Even with severe signal degradation in CI signal processing, CI users can obtain excellent open-set speech recognition scores in quiet, but substantial individual variability in speech recognition outcomes remains (Gifford, Shallop, & Peterson, 2008).

The candidacy criteria for cochlear implantation includes requirements for minimum audiometric pure-tone thresholds and speech recognition scores. A person's chronological age is usually not a factor that is considered during a CI candidacy evaluation. This is because the amount of *benefit* a person receives from a CI, defined as the improvement in post-implantation speech recognition scores compared to pre-implantation scores, is not impacted by age (Labadie, Carrasco, Gilmer, & Pillsbury, 2000; Pasanisi et al., 2003; UK Cochlear Implant Study Group, 2004). Furthermore, quality-of-life measures are significantly improved in older adults after receiving a CI (Vermeire et al., 2005). However, post-implantation performance in older CI users can be worse when compared to younger CI users (Blamey et al., 2013; Friedland, Runge-Samuelson, Baig, & Jensen, 2010; Roberts, Lin, Herrmann, & Lee, 2013; Sladen & Zappler, 2015). Older CI candidates may have poorer pre-implantation scores than younger candidates, which could ultimately result in a substantial performance gap between younger and older CI users.

Several studies that compared groups of younger and older CI users on speech perception measures found no significant differences in performance between age groups (Haensel, Ilgner, Chen, Thuermer, & Westhofen, 2005; Labadie et al., 2000; Leung et al., 2005; Noble, Tyler, Dunn, & Bhullar, 2009; Park, Shipp, Chen, Nedzelski, & Lin, 2011; Pasanisi et al., 2003; Poissant, Beaudoin, Huang, Brodsky, & Lee, 2008). Pasanisi et al. (2003) compared post-implantation word and sentence recognition scores in quiet between CI users ≥ 65 years old and a control group of CI users < 60 years old. The mean duration of deafness was consistent across groups. The mean word and sentence recognition scores were approximately 73% in the older group and 84% in the control group. No significant differences were found for word or sentence recognition scores between age groups. One potential reason for this result is the age of the participants in the control group; the older group consisted of CI users between 65 and 74 years of age (mean=66.8 years), while the control group included CI users between 41 and 59 years of age (mean=51.2 years). Age-related changes in auditory perception can be observed as early as middle age (Grose, Hall, & Buss, 2006; Snell & Frisina, 2000). Therefore, it could be argued that participants in the control group were not effectively “younger” than the older group. In fact, essentially all of the studies that concluded that there was no significant effect of age on post-implantation speech recognition performance had younger/control groups that included individuals between 45 and 60 years of age. Another reason for the lack of significant differences between groups could be because of the choice of test materials, which tended to be relatively easy sentence recognition tasks presented in quiet, and thus ceiling effects might have diminished differences between age groups.

Many studies that evaluated the impact of age on CI performance on relatively difficult speech recognition measures revealed a significant effect of age (Chatelin et al., 2004; Friedland et al., 2010; Sladen & Zappler, 2015). Sladen and Zappler (2015) measured speech recognition scores on multiple word and sentence recognition tests in quiet and in noise for an older group (mean=70.7 years) and a younger group (mean=39.7 years). Results showed that the older group performed significantly worse than the younger group on all speech recognition measures. The largest group differences were observed in the speech-in-noise conditions with the worst signal-to-noise ratios (i.e., the most difficult conditions resulting in the poorest performance). It is possible that age differences in word or sentence recognition may only be observed for more difficult tasks (e.g., Dubno, Dirks, & Morgan, 1984).

This is not to say that CIs are not beneficial to older users. Cochlear implantation in individuals >65 years old is associated with significant improvements in speech recognition scores and quality-of-life measures (Horn et al., 1991; Shin et al., 2000; Vermeire et al., 2005; Waltzman, Cohen, & Shapiro, 1993). However, if older CI users perform more poorly than younger CI users on everyday speech recognition tasks, then there is a need to examine the source of this outcome and identify solutions to improve performance specifically for older people.

Studies that measured the effect of age at implantation invariably found that duration of deafness (DoD), or the length of severe-to-profound hearing loss prior to implantation, was a stronger predictor of CI performance than age (Budenz et al., 2011; Leung et al., 2005). Budenz et al. (2011) compared CI users who were ≥70 years of age to CI users between 18 and 69 years of age on multiple speech recognition measures. The older group performed significantly worse than the younger group; however, the effect of age was no longer significant when participants' DoD was considered in the analysis. Moreover, Blamey et al. (2013) assessed the contribution of various factors to CI performance; the strongest predictors (in order of largest to smallest effect) were duration of CI experience, age at onset of deafness or age at implantation, DoD, and etiology of hearing loss. The effect of age alone, when controlling for DoD, contributed to a small amount of the variance in CI outcomes. Individuals implanted after the age of 70 years had poorer speech recognition outcomes than individuals implanted before age 70. In summary, it is apparent that advanced age can negatively impact CI performance, especially when comparing older CI users to much younger CI users on difficult speech recognition tasks. However, other variables, including DoD, appear to be stronger predictors of post-implantation CI performance. The individual contributions of aging and DoD *per se* to post-implantation CI performance, as well as the interaction between these factors, is not well understood.

Peripheral Neural Survival and CI Outcomes

Prolonged DoD is associated with poorer CI outcomes compared to users with shorter DoDs (Blamey et al., 2013; Holden et al., 2013; Lazard et al., 2012; Leung et al., 2005). Extended periods of auditory deprivation, as occurs with prolonged DoDs, can cause peripheral, central, and cortical changes that limit an individual's ability to encode and process speech received through a CI. At the level of the periphery, prolonged DoD causes degeneration of spiral ganglion cells (SGCs), ultimately resulting in a substantial loss SGCs in the peripheral auditory system in animal models (Leake, Hradek, & Snyder, 1999). In the central system, long DoDs cause changes to the structure and function of the ascending central auditory pathway. These include significant reductions in the anteroventral and ventral cochlear nucleus neurons and medial nucleus of the trapezoid body, as well as similar reductions in the superior olivary complex, lateral lemniscus, and inferior colliculus (Nishiyama, Hardie, & Shepherd, 2000; Pasic, Moore, & Rubel, 1994; Shepherd & Hardie, 2001; Shepherd, Roberts, & Paolini, 2004). At the cortical level, CI users who reported longer DoDs prior to implantation had smaller regions of auditory-cortex activation following implantation compared to CI users with shorter DoDs (Green, Julyan, Hastings, & Ramsden, 2005). This result is consistent with other studies that have demonstrated significant decreases in auditory cortical activity with increasing periods of deafness (Ito, Iwasaki, Sakakibara, & Yonekura, 1993).

In regards to CI users, the loss of SGCs in the peripheral auditory system appears to result in a relatively poor electrode-to-neural interface. The electrode-to-neural interface refers 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) and electrode configuration (Bierer & Faulkner, 2010). 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 dynamic ranges and steeper loudness growth functions, which may diminish performance with a CI (Bierer & Nye, 2014).

While prolonged DoD prior to implantation has a strong relationship to SGC survival, advancing age is also associated with a widespread loss of SGCs in animal models, even in the absence of peripheral hearing loss (Kujawa & Liberman, 2015; Liberman, 2015; Makary, Shin, Kujawa, Liberman, & Merchant, 2011; Sergeyenko, Lall, Liberman, & Kujawa, 2013). If the same is true in humans, older CI users with and without prolonged DoD may experience some degree of SGC loss, which could impact post-implantation performance. However, the relationship between the number of surviving SGCs (i.e., peripheral neural survival) and CI performance remains unclear. In fact, no correlations have been found between speech recognition ability with a CI and SGC counts (Aayesha M. Khan et al., 2005; Nadol et al., 2001). This suggests a separate mechanism that may underlie the performance gap between younger and older CI users, such as age-related central auditory temporal processing deficits.

Age-related Central Auditory Temporal Processing Deficits

Another factor that could limit an older CI user's performance in addition to poor peripheral neural survival is the presence of age-related central auditory temporal processing deficits. Although temporal processing deficits are well-documented in the aging literature, studies that measure temporal acuity in CI users typically do not consider age as a contributing factor. CI users can demonstrate comparable temporal processing abilities to normal-hearing listeners (e.g., Shannon, 1989), but there is considerable individual variability in CI users' temporal resolution. Older acoustic-hearing adults, independent of their hearing sensitivity, show deficits compared to younger adults on behavioral temporal processing tasks including gap detection (Snell & Frisina, 2000), duration discrimination (Fitzgibbons & Gordon-Salant, 1994, 1995), time-compressed speech recognition (Fitzgibbons & Gordon-Salant, 1996; Gordon-Salant & Fitzgibbons, 1993), and processing of envelope modulations (He, Mills, Ahlstrom, & Dubno, 2008). Electrophysiological measures have also revealed temporal envelope processing deficits at the central and cortical levels in older normal-hearing listeners (Leigh-Paffenroth & Fowler, 2006; Purcell, John, Schneider, & Picton, 2004). Additionally, neural correlates of age-related temporal processing deficits using animal models have been identified in the inferior colliculus for the encoding of temporal gaps (Walton, Frisina, Ison, & O'Neill, 1997) and amplitude modulations within the temporal envelope (Shaddock Palombi, Backoff, & Caspary, 2001).

CI users must rely primarily on temporal envelope cues to understand speech because of the severe spectral degradation that is introduced during CI signal processing (e.g., Shannon et al., 1995). Despite this well-known reliance on temporal information to understand speech through a CI, psychoacoustical studies in CI users do not consider age-related temporal processing deficits as a possible factor contributing to individual variability in performance. Based on the behavioral, electrophysiological, and physiological evidence from the aging literature, it is reasonable to assume that declines in auditory temporal processing in older CI users could limit their ability to perceive speech signals.

Cognition and CI Outcomes

Age-related changes in cognition have been proposed as a potential factor influencing CI performance in older individuals (e.g., Schvartz, Chatterjee, & Gordon-Salant, 2008). Older adults often experience declines in their working memory ability (Baddeley, 2012; Daneman & Carpenter, 1980), selective attention (Humes, Lee, & Coughlin, 2006), and cognitive processing speed (Park et al., 1996). Older acoustic-hearing listeners, regardless of their hearing status, perform more poorly than younger listeners when presented with speech in background noise (Dubno et al., 1984; Pichora-Fuller, Schneider, & Daneman, 1995), which could be associated with age-related declines in cognitive processing (Gordon-Salant & Cole, 2016). Speech-in-noise, as well as speech information provided through a CI, can both be considered degraded signals. CI-processed speech information is severely degraded due to a loss of spectral information and temporal fine structure, as well as a frequency shift due to shallow insertion of the electrode array (Loizou, 2006). The recognition of degraded speech signals (i.e., speech in noise) depends, in part, on a listener's cognitive ability in the domains of working memory (Wingfield & Tun, 2001), selective attention (McCoy et al., 2005), and cognitive processing speed (Brébion, 2003). Thus, age-related cognitive decline could negatively impact an older individual's ability to process degraded speech received through a CI. Support for this idea was found in a study by Schvartz et al. (2008) that measured CI-simulated (vocoded) phoneme recognition in younger, middle-aged, and older normal-hearing listeners. When stimuli were severely degraded by limited spectral channels and a greater frequency shift, younger listeners had better phoneme recognition than middle-age and older listeners. Age of the listener and working memory ability were the primary predictors of vowel recognition performance.

Summary and Hypotheses

In summary, the ability to accurately encode temporal information is critical to speech recognition through a CI. The central hypothesis of this research is that there is an effect of advancing age on the perception of electrical signals delivered by a CI. Current approaches to the design and programming of CIs essentially ignore the impact of age on the auditory system, and as a result, CI manufacturers do not have age-specific programming strategies for older CI users. This is despite the fact that aging is accompanied by substantial changes to the auditory system. Because of these changes and the resulting limitations in auditory processing, default stimulation settings may not always be optimal for older CI users and may not provide maximum speech recognition benefits. The impact of age-related auditory temporal processing deficits on CI performance is unknown, and it is unknown how such deficits should be accommodated in the programming of a CI to optimize speech recognition.

The factors that were hypothesized to contribute to an age limitation in adult CI users were: (1) age-related reductions in peripheral neural survival resulting in a poor electrode-to-neural interface, (2) underlying age-related auditory temporal processing deficits, and (3) age-related declines in cognitive processing ability. Studies 1 and 2 were designed to establish the presence of age-related central auditory temporal processing deficits for non-speech signals. Study 1 utilized simple, static measurements of temporal processing, while Study 2 used more complex and dynamic signals. Study 3 was designed to bridge the gap between those psychophysical measurements that utilized non-speech signals to CI users' functional performance with their CIs by using speech signals.

The goal of this research was to identify age-related auditory temporal processing deficits using different electrical stimulation parameters and to estimate the relative contributions of age and peripheral neural survival to those deficits. All experiments utilized a variety of stimulation parameters, including multiple electrical stimulation rates and envelope modulation frequencies, in order to determine if older CI users' performance could be improved under certain stimulation conditions. Peripheral neural survival was estimated by calculating the slope of electrically evoked compound action potential (ECAP) amplitude growth functions on individual electrodes. Steeper ECAP slopes are indicative of greater peripheral neural survival (i.e., a greater number of surviving SGCs) (Hall, 1990; Smith & Simmons, 1983). Auditory temporal processing ability was examined for detection of gaps (Study 1) and detection of amplitude modulation (Study 2) on single electrodes. Recognition of consonants presented within monosyllabic words varying in discrete temporal cues (Study 3) was tested to evaluate functional temporal processing. Cognitive processing ability, including speed of processing, working memory, and attention, was tested using standardized, non-auditory measures.

All experiments utilized direct stimulation methods to measure auditory temporal processing ability in CI users. Direct stimulation procedures bypassed participants' external sound processors and controlled stimulation to the electrode array using a computer. This method allowed for precise stimulation at the single-electrode level. The results were expected to provide insight into the potential underlying age-related temporal processing deficits experienced by older CI users. Age-related temporal processing deficits may explain why older CI users, and those with relatively poor neural survival due to age and/or prolonged deafness, do not achieve comparable post-implantation performance to younger CI users.

Study 1: Effect of Age on Gap Detection Thresholds in CI Users

Introduction

Temporal processing of silent gaps.

The ability to accurately process temporal changes within acoustic signals, and ultimately the ability to process temporal speech cues, is critical for the perception of speech through a CI (Cazals, Pelizzone, Kasper, & Montandon, 1991; Sagi, Kaiser, Meyer, & Svirsky, 2009; Tyler, Moore, & Kuk, 1989). In fact, better gap detection ability has been associated with better speech recognition scores in CI users using a variety of speech materials (Cazals et al., 1991; Gantz, Woodworth, Knutson, Abbas, & Tyler, 1993; Hanekom & Shannon, 1998; Muchnik, Taitelbaum, Tene, & Hildesheimer, 1994; Tyler et al., 1989). This is likely because CI signal processing results in degraded spectral information, which forces CI users to rely on temporal information within the signal to understand speech (Shannon et al., 1995). The detection of short, silent gaps within acoustic signals is a simple, non-speech measure of temporal resolution (Plomp, 1964). The gap detection threshold (GDT) is a psychoacoustic measurement that is widely used to quantify static temporal acuity (Walton, 2010). The current study measured GDTs in younger, middle-aged, and older CI users with the intent of establishing a profile of age-related central auditory processing deficits for simple, non-speech stimuli.

The detection of a gap is thought to involve higher-level auditory processes that integrate, or “smooth,” the temporal characteristics of incoming auditory signals over a short time period or window of between 200-300 ms (i.e., temporal integration) (Zwislocki, 1960). A temporal integration time window results in a reduction in the magnitude of rapid temporal amplitude changes and a preservation of slow temporal changes. The integration window has been modeled as a “sliding temporal integrator” in which temporal changes are averaged over the duration of the window in real time (Moore, Glasberg, Plack, & Biswas, 1988; Plack & Moore, 1990). The output of the temporal integrator represents a weighted average of the real-time input. Output falling within the center of this time window is weighted more heavily, and is more prominently conveyed within the “internal representation” of the signal (i.e., the neural response resulting from an input signal), compared to the output falling further away from the center. In the case of a continuous signal with a brief gap inserted into the middle of the signal, the output of the temporal integrator is first expected to build up gradually in response to the onset of the signal. In response to the short gap, the averaged output would reflect a dip in amplitude, with the size of the dip dependent on the duration of the gap. The output will then return to its original amplitude following the offset of the gap and will gradually decay after the offset of the entire signal. The dip in the output of the temporal integrator is theorized to cue the detection of a silent gap in an acoustic signal. In this way, the ability to detect a gap within an otherwise continuous signal is considered to be a measure of the decay of auditory sensation within the central auditory system (Penner, 1977). The process of the sliding temporal integrator for multiple example input signals is illustrated in Figure 1. The input and response output from the integrator for a brief gap inserted into a signal is also shown in Figure 1 (panel C). Thus, temporal resolution (as measured with a gap detection task) is determined by the input signal encoded by the auditory nerve and by the duration of the temporal integration window.

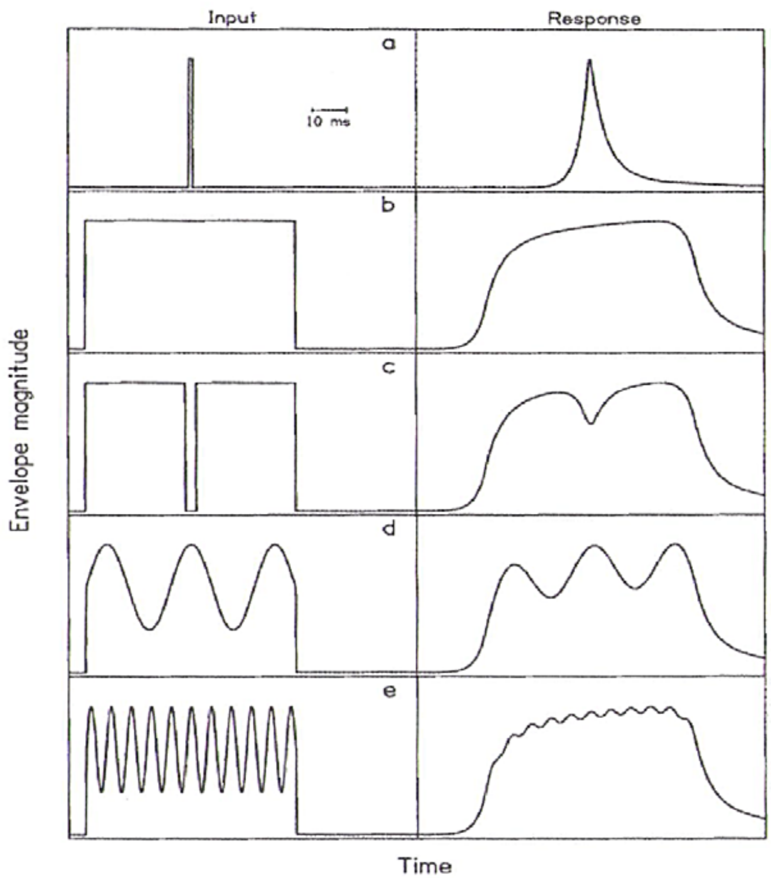


Figure 1. Taken from Moore (2012). Examples of the sliding temporal integrator. Left panels represent the acoustic input to the temporal integrator. Right panels represent the corresponding outputs. Time window duration is 100 ms.

Gap detection ability in acoustic-hearing listeners.

Signal-related factors.

GDT, defined as the duration of the shortest detectable gap of silence within an otherwise continuous signal, is affected by signal-related factors including the type of signal, the spectrum of the signal, and the presentation level. The detection of gaps in sinusoids is dependent on the starting phase of the signal following the offset of the gap, which is likely due to ringing within an auditory filter (Shailer & Moore, 1987). GDTs for narrowband noises are dependent on the bandwidth of the noise signal because of the random fluctuations inherent to the noise itself. Narrow bandwidths result in slower amplitude fluctuations, which make the detection of a temporal gap more difficult because it is more likely to be confused with the random dips already present in the signal. Wider bandwidths, or broadband noise, allow for more rapid amplitude fluctuations in the signal, making the gap less confusable with these inherent fluctuations, resulting in better GDTs (Glasberg & Moore, 1992; Shailer & Moore, 1987). Increasing the signal bandwidth beyond that of a single auditory filter also results in better GDTs (Eddins, Hall, & Grose, 1992; Grose, 1991), indicating a benefit from comparing the output from multiple auditory filters. When monitoring the output across more than one auditory filter, the random amplitude fluctuations within the noise signal will differ at each auditory filter, but the temporal gap itself will be consistent across all filters, making it less likely to be confused with the random dips in the noise. This across-channel monitoring may explain why the choice of center frequency, or the bandwidth of a single auditory filter, does not directly limit gap detection ability.

GDTs are also dependent on the presentation level of the signal. Because gap detection is considered a measure of the decay of auditory sensation, a gap will only be detected when auditory sensation changes at or above the threshold for intensity discrimination (Penner, 1977; Plomp, 1964). In this sense, gap detection tasks are closely related to intensity discrimination, or the ability to detect an increase or decrease in signal intensity. Intensity discrimination thresholds are higher (worse) for signals presented at low presentation levels near threshold compared to signals presented at the most comfortable level (MCL) (Miller, 1947). Similarly, GDTs are elevated (worse) when signals are presented at levels near audiometric threshold compared to when presented at a higher intensity level, because of increasing intensity discrimination thresholds at soft levels (Moore, Peters, & Glasberg, 1993). In summary, signal-related factors, such as the spectrum and bandwidth of the signal and the presentation level, have significant effects on GDTs. However, listener-related factors, primarily the age of the listener, can also impact gap detection ability.

Listener-related factors.

In young normal-hearing listeners, average GDTs can be as small as 2-3 ms in duration (Plomp, 1964). GDTs significantly worsen with increasing age in normal-hearing listeners (Schneider, Pichora-Fuller, Kowalchuk, & Lamb, 1994; Snell, 1997). Poorer GDTs are also observed in listeners of all ages who have sensorineural hearing loss compared to normal-hearing listeners (Fitzgibbons & Wightman, 1982; Florentine & Buus, 1984; Tyler, Summerfield, Wood, & Fernandes, 1982). In many cases, age-related elevations in GDTs can be explained by elevated audiometric thresholds in older participants. However, studies that investigated the independent effects of hearing loss and age on

GDTs found that gap detection ability declines with age independent from peripheral hearing status.

Schneider et al. (1994) presented gaps between two Gaussian-enveloped 2000-Hz tone pulses to younger and older listeners with normal audiometric thresholds. GDTs of the older listeners were nearly twice as large as the thresholds in younger adults and showed more variability between participants. Similarly, Snell (1997) measured gap detection in noise bursts in younger and older participants who were matched on the basis of audiometric thresholds. Results indicated that GDTs obtained by the older participants were larger compared to the GDTs of younger participants. Additionally, the location of the gap within the continuous signal has an effect on GDTs in older listeners. Poorer GDTs were observed in older listeners for gaps falling close to the onset or offset of the signal compared to when the gap is located in the center of the signal (He, Horwitz, Dubno, & Mills, 1999), which suggested that older listeners were exhibiting deficits in temporal resolution beyond what could be explained simply by age-related changes to the peripheral system.

Gap detection ability in CI users.

Signal-related factors.

For acoustic-hearing listeners, temporal resolution is impacted by the filtering characteristics of the peripheral auditory system, which has been modeled as a series of bandpass filters with bandwidths that increase as center frequency increases (Duifhuis, 1973). Thus, changes in GDT with different stimulus frequencies can theoretically be explained by the ringing characteristics of auditory filters (e.g., Fitzgibbons & Wightman, 1982). However, because older listeners displayed reduced temporal resolution beyond what can be explained by age-related changes to the periphery, temporal resolution is also likely mediated by the central auditory system. In electrically stimulated ears, the typical filtering performed by the cochlea is removed and replaced by tonotopically spaced electrode contacts that stimulate the SGCs directly. Electrical stimulation also results in a limited electrical dynamic range, increased nerve fiber synchrony, and a removal of all basilar membrane filtering and compression (Kiang & Moxon, 1972; Sachs, Young, & Miller, 1983). Therefore, CI users' temporal acuity is likely dependent on both the quality of the electrode-to-neural interface and resolution within the central auditory system.

CI users are able to obtain GDTs comparable to those obtained by normal-hearing, acoustic listeners (Dobie & Dillier, 1985; Moore & Glasberg, 1988; Shannon, 1989). Much of the previous literature investigating gap detection ability in CI users evaluated the effect of signal-related factors on GDTs, such as presentation level, place of stimulation (electrode location), and electrical stimulation rate. Just as in normal-hearing listeners, CI users showed similar patterns of gap detection ability with varying presentation level: GDTs were significantly elevated for lower levels compared to higher presentation levels (Chatterjee, Fu, & Shannon, 1998; Moore & Glasberg, 1988; Preece & Tyler, 1989; Shannon, 1989), likely due to the accompanying differences in intensity discrimination thresholds at low levels. On average, GDTs improved by an order of magnitude when presented at 15 dB above hearing thresholds compared to when stimuli were presented near threshold, both for stimuli presented via soundfield to clinical sound processors or via direct stimulation of the electrode array. This is unsurprising given that intensity discrimination ability in CI users declines with decreasing intensity level (Chua, Bachman, & Zeng, 2011; Pfingst, Burnett, & Sutton, 1983), which is consistent with intensity discrimination thresholds obtained from acoustic listeners (Miller, 1947).

Stimulus frequency has little effect on gap detection ability in CI users (Moore & Glasberg, 1988; Shannon, 1989), whereas in acoustic-hearing listeners, gap detection is mediated by auditory filter bandwidth and the ringing of auditory filters. In CI users, basilar membrane filtering and other cochlear contributions to gap detection ability are bypassed. Therefore, because basilar membrane filtering does not occur in CI users, the tonotopic place of stimulation would not be expected to impact gap detection ability. However, GDTs can vary across electrode locations within individuals (Bierer, Deeks, Billig, & Carlyon, 2015), but these patterns are not consistent across different listeners. Thus, GDTs may be related to the local neural population interfacing with a particular electrode location (i.e., the electrode-to-neural interface), rather than tonotopic-specific properties of auditory encoding.

Another signal-related factor that may impact gap detection ability is the electrical stimulation rate delivered to single electrodes. The difference between low- and high-rate stimulation is the time interval between individual pulses, or the inter-pulse interval (IPI); the IPI is longer in low-rate stimulation and shorter in high-rate stimulation. For lower stimulation rates ≤500 pulses per second (pps), the long IPI could present a level of uncertainty in discriminating between the IPI and a short temporal gap, which may cause GDTs to be elevated at low stimulation rates. This is akin to a temporal gap being more difficult to detect when inserted into an acoustic signal with slow-moving amplitude fluctuations because it could easily be confused with the random dips already present in the signal (Eddins, Hall III, & Grose, 1992). Alternatively, the short IPIs that compose high-rate electrical stimulation (≥1000 pps) could limit gap detection ability when the interval approaches the neural refractory period, or the time it takes for a single nerve fiber to recover after firing. This could result in poor transmission of a temporal gap within high-rate stimulation if the fibers that are required to respond to the onset of the signal following the gap are unable to fire because of refractory limitations.

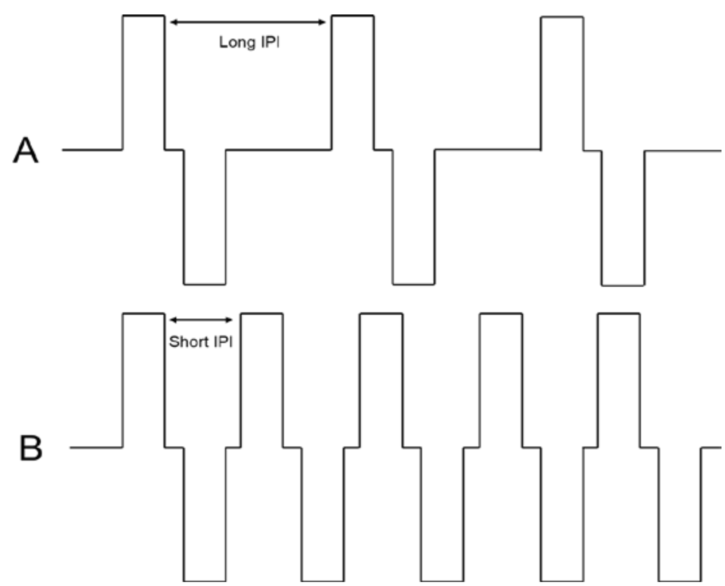


Figure 2. Schematic example of differences in IPI between pulse trains presented at relative slow stimulation rates (A) and fast stimulation rates (B).

Listener-related factors.

Listener-related factors may also impact GDTs in CI users, which may explain some of the substantial individual variability observed in gap detection experiments (e.g., Preece & Tyler, 1989). In particular, age at onset of hearing loss and DoD, both of which are likely correlated with SGC survival, are predictive of gap detection performance in CI users (Bierer et al., 2015; Busby & Clark, 1999). In other words, gap detection ability in CI users is likely affected by peripheral neural survival. Busby and Clark (1999) measured GDTs in adolescents and young adult CI users who had early onsets of hearing loss (before four years of age). There was a negative correlation between age at onset of profound hearing loss and GDTs, suggesting that participants with the earliest onsets of hearing loss had the poorest gap detection performance. Bierer et al. (2015) showed that individuals with longer DoDs, and presumably poorer neural survival, had poorer GDTs compared to individuals with shorter DoDs.

Gap detection ability, and the impact of signal-related and listener-related variables, has been studied extensively in individuals with CIs, although it is not commonly studied within the context of auditory aging. Despite the evidence suggesting declines in gap detection performance as a function of age for acoustic-hearing listeners, age is rarely evaluated as a potential factor impacting GDTs in CI users. In order to evaluate the effect of age on gap detection ability, the impact of other listener-related variables, including DoD and peripheral neural survival, must be taken into account.

In the current study, electrophysiological techniques were used to probe the electrode-to-neural interface to control for potential peripheral differences in neural survival between younger and older participants. The assessment of the ECAP is advantageous because it can be measured across the electrode array easily and non-invasively in CI users. ECAPs reflect the synchronous firing of SGCs at a specific electrode location in response to electrical stimulation. The input-output functions (amplitude growth functions [AGFs]) of ECAP amplitude in response to increasing current level can be used as a predictor of peripheral neural survival, with steeper AGFs indicating more surviving SGCs at a particular electrode location (Cohen, 2009; Hall, 1990; Smith & Simmons, 1983). Each nerve fiber is thought to contribute equally to the response, which represents a "unitary response concept" for SGCs (Goldstein Jr & Kiang, 1958). Thus, the greater the number of SGCs responding to electrical stimuli, the steeper the resulting ECAP AGF. In addition to SGC loss, neural degeneration within the peripheral system can alter the temporal discharge patterns of electrically stimulated SGCs, especially at fast stimulation rates (Shepherd & Javel, 1997). Thus, poor neural survival in CI users may limit the ability of the auditory nerve to encode a temporal gap, regardless of age.

Summary and hypotheses.

The goal of Study 1 was to identify the effect of age among CI users on gap detection ability at a variety of electrical stimulation rates. The contribution of other potential age-related covariates to age (i.e., peripheral neural survival) to GDTs was also measured. It was hypothesized that older CI participants (OCI) would demonstrate poorer GDTs compared to younger CI (YCI) participants, because of age-related auditory temporal processing limitations. OCI participants were also hypothesized to have shallower ECAP AGFs compared to YCI participants due to age-related reductions in SGCs. The age differences in GDTs were hypothesized to be largest for faster stimulation rates (≥1000 pps) due to altered temporal discharge patterns of SGCs as a result of age-related neural degeneration and loss of SGCs.

Method

Participants.

Thirty CI users were recruited to represent a wide range of ages across the adult lifespan. Participants' ages ranged from 20-83 years (mean=54.3 ± 19.1 years). Participant demographics are provided in Table 1. All participants passed a cognitive screening for dementia with a score of ≥22 on the Montreal Cognitive Assessment (MoCA) (Nasreddine et al., 2005). A MoCA score of 22-25 indicates that an individual is at risk for mild cognitive impairment (Cecato, Martinelli, Izbicki, Yassuda, & Aprahamian, 2016). Being considered at risk for mild cognitive impairment did not preclude anyone from participating in this study because (1) participants' age is of primary importance in this experiment and (2) excluding older potential participants who are considered at risk of cognitive impairment, many of whom were in their 80s, would limit the recruiting potential for older participants. Additionally, it is not clear if the traditional MoCA is a valid screening tool for individuals with hearing loss because many tasks require auditory recognition of test items (Lin et al., 2017). All participants were implanted with Cochlear-brand devices, primarily with perimodiolar electrode arrays, which are intended to sit in close proximity to SGCs and make electrophysiological measurements more feasible. Electrophysiology was used to estimate each participant's degree of peripheral neural survival, which was expected to impact behavioral measurements. All participants were required to have at least one year of CI experience to ensure stable responses and tolerance to electrical signals (Hughes et al., 2001).

Table 1.
Participant Demographic Table: Study 1.

Participant	Age	Gender	Age at HL Onset	DoD	Etiology	Device
CCG	20	M	0	20	Unknown	CI422
CDE	23	M	0	12	Connexin 26	CI24RE(CA)
CAR	24	M	4	14	Hereditary	CI24RE(CA)
CBX	27	F	0	22	Waardenburg Syndrome (Type 2)	CI24RE(CA)
CDA	27	F	0	20	Connexin 26	CI512(CA)
CAT	29	M	10	9	Hereditary	CI24RE(CA)
CDF	30	F	0	16	Hereditary	CI24RE(CA)
CBP	37	F	5	15	Hereditary	CI24M
CCS	41	M	1	37	Meningitis	CI422
CBW	45	M	26	5	COGAN Syndrome	CI24R(CS)
CAP	50	F	38	1	Hereditary	CI24RE(CA)
CAS	54	F	41	3	Hereditary	CI24RE(CA)
CAW	54	M	0	47	Unknown	CI24RE(CA)
CCF	55	F	48	5	Unknown	CI422
CAQ	58	F	22	29	Unknown	CI24RE(CA)
CBK	58	F	20	31	Unknown	CI24RE(CA)
CBF	59	M	5	47	Hereditary	CI24RE(CA)
CBG	64	F	4	53	Rh Incompatibility	CI512(CA)
CAJ	65	F	0	47	Unknown	CI24M
CBR	65	F	0	57	Unknown	CI24RE(CA)
CCR	69	F	2	60	Measles	CI24RE(CA)
CAK	70	M	57	2	Unknown	CI24R(CS)
CAF	71	F	5	49	Unknown	CI24RE(CA)
CAM	72	F	40	24	Unknown	CI24RE(CA)
CAO	72	F	3	63	Rheumatic fever	CI512(CA)
CBT	75	F	50	20	Unknown	CI24RE(CA)
CCA	76	M	70	1	Ototoxicity	CI512(CA)
CAD	77	M	55	10	Unknown	CI24RE(CA)
CBC	79	F	35	41	Unknown	CI24RE(CA)
CBB	83	M	77	2	Aging	CI24RE(CA)

Note. HL=hearing loss; DoD=duration of deafness.

Stimuli and procedure.

Gap detection thresholds.

All stimulus presentation was performed with direct stimulation of the CI electrode array using the Nucleus Implant Communicator (NIC2) and a Cochlear-brand L34 research sound processor. Direct stimulation procedures bypass participants' external sound processors and control stimulation to the electrode array using a computer. This method allows for precise stimulation at the single-electrode level. Experimental stimuli were 300-ms constant-amplitude pulse trains with a 25-µs phase duration and an 8-µs interphase gap. Monopolar stimulation was used. GDTs were measured for five single electrodes (E4 [basal], E8, E12, E16, and E20 [apical]) at three stimulation rates (500, 1000, and 4000 pps) using a three-interval, two-alternative forced choice adaptive procedure (Levitt, 1971). The three-down, one-up adaptive procedure, which targeted a 79.4% threshold level, was terminated after ten reversals with the GDT calculated as the mean of the last six reversals. The initial gap duration was 100 ms and decreased by a factor of five until the first two reversals, after which the gap duration was decreased by a factor of two. This procedure was repeated at least three times for each condition on each electrode, and more trials were tested if the GDT between trials varied by more than 2 ms. The final GDT for each electrode was an average of the results of all three runs. The gaps were inserted into the pulse-train stimuli by deleting a number of individual pulses from the middle of the target stimulus to create silent gaps of varying duration. Direct stimulation best practices were followed to perform the experiments (Litovsky, Goupell, Kan, & Landsberger, 2017). The pulse-train stimuli were presented at the most comfortable level (MCL) for each electrode as reported by the participant. MCL was measured using standard CI mapping procedures for each test electrode for every stimulation rate. No feedback was provided to participants. The presentation of stimuli was blocked for different stimulation-rate conditions; the order of the electrodes tested in each rate block was randomized.

The order of the conditions and electrodes tested was randomized across participants.

ECAP amplitude growth functions (AGFs).

In order to isolate age-related changes in temporal processing ability due to reduced neural survival or a poor electrode-to-neural interface, ECAP AGFs were measured at the same five electrode locations that were tested in the behavioral measurements using research processors and Custom Sound EP software provided by Cochlear Ltd. A screenshot of the software and ECAP tracings corresponding to the AGF is shown in Figure 3. ECAPs reflect the synchronous firing of spiral ganglion neurons at a specific electrode location in response to electrical stimulation. The input-output functions of ECAP peak-to-peak amplitude in response to increasing current level is a predictor of peripheral neural survival, with steeper AGFs indicating more surviving spiral ganglion cells (Smith and Simmons, 1983; Hall, 1990). ECAP measurements used the forward-masking procedure (Abbas *et al.*, 1999) with an 80-pps probe rate, 50-µs phase duration, and a 7-µs interphase gap. The masker pulse had the same stimulation parameters as the probe pulse with a +10 clinical unit (CU) offset in input level (the masker pulse was 10 CUs higher than the probe pulse). This procedure takes advantage of the refractory properties of auditory nerve fibers to measure the relatively small neural response without signal artifact. ECAP stimulation parameters were the same for all electrode locations and all participants. Consistent stimulation parameters are needed to make comparisons in neural survival across different participants, as well as across different electrode locations within the same participant. 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.

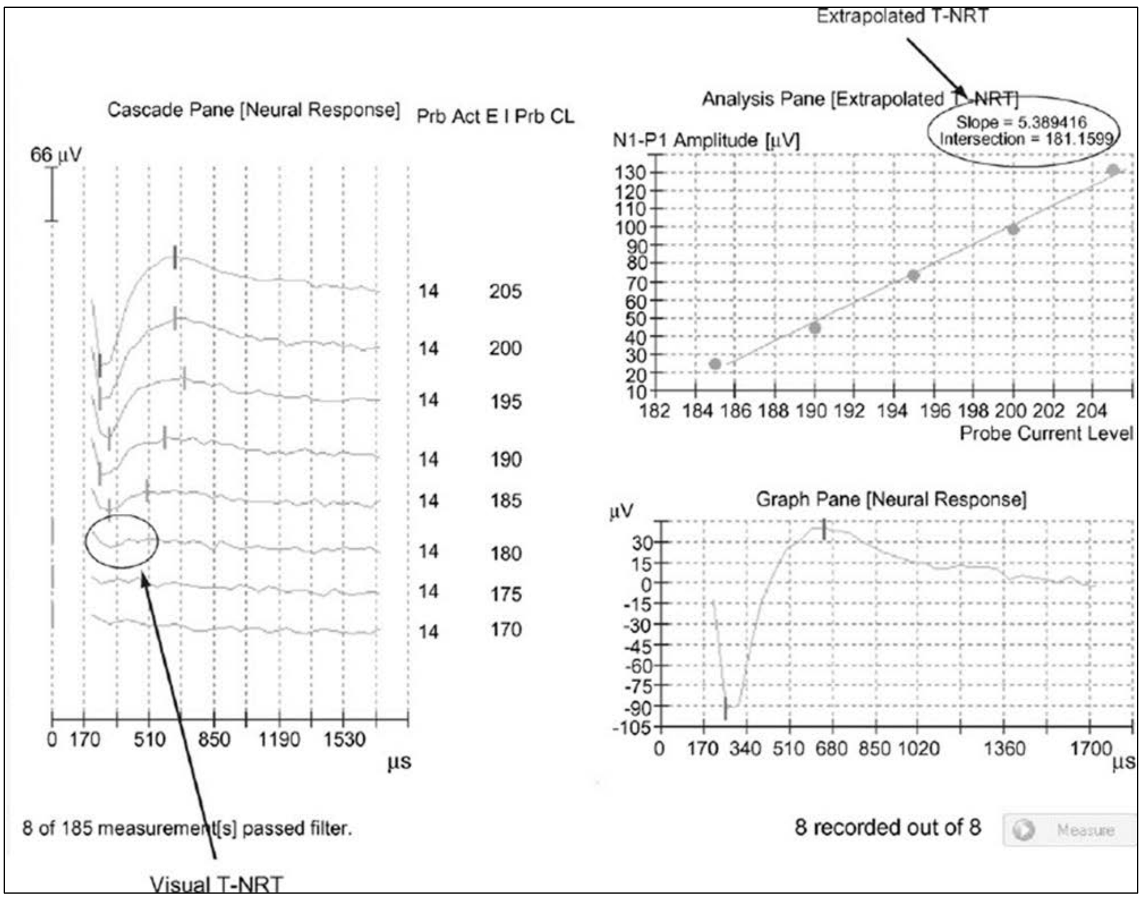


Figure 3. Screenshot of Custom Sound EP software used for collection of ECAPs. A series of individual tracings are shown on the left. The visual ECAP threshold (T-NRT) is circled on the left panel, which shows the lowest input level that elicited a clear negative peak. The top right panel reflects the input/output function from the series of recordings on the left. The resulting slope of the input/output function and the extrapolated threshold is circled in the top right panel. The bottom right panel shows an individual trace for a single input level with the marked negative and positive peaks.

Statistical analysis.

A 3-level linear mixed-effects (LME) model was used to examine the effects of stimulation rate, chronological age, age at onset of hearing loss, duration of deafness, and ECAP AGF slope on GDTs. The model building approach followed the recommendations by Hox, Moerbeek, and Van de Schoot (2017). First, an intercept-only model was used as a benchmark. Second, the stimulation rate variable [three levels: -1 = 500 pps, 0 = 1000 pps (reference level), 1 = 4000 pps] was added as a level-1 predictor to the fixed effects structure. The improvement in model fit with the addition of this fixed effect variable was compared to the intercept-only model with a χ^2 significance test (α level = 0.05). Next, the main effects and interactions for all level-2 predictors (age, age at onset, duration of deafness, and ECAPs) were added to the fixed effects. Values for all level-2 predictors were transformed into standardized values (z-scores) before being entered into the model. Thus, results for level-2 predictors represent changes to GDTs with increasing or decreasing a particular variable on a standard deviation (SD) scale. Non-significant level-2 predictors were then removed to create the most parsimonious fixed effects structure.

The random effects were structured to represent a 3-level model in which the multiple electrode locations were nested within subject. Because each subject was tested at five electrode locations, measurements at the electrode level are not independent of one another. Therefore, by specifying that electrodes were nested within subjects, ECAP slopes could be added to the model as a level-2 predictor. In this way, ECAP slopes for individual electrodes were recognized as an attribute of that electrode within its respective subject.

Next, random slope variation for the level-1 predictor (stimulation rate) was added to the model. The model failed to converge when random slopes were added to the random effects and as a result, the random effects for the final model include only intercept variation for subjects and for electrodes nested within subjects. Lastly, cross-level interactions (interactions between fixed level-1 and level-2 predictors) were added to the fixed effects structure. In order to appropriately interpret these interactions, both the main effect and any lower-level interaction term remained in the model regardless of significance.

Results

Effects of stimulation rate, ECAPs, and age.

Average GDTs obtained at each stimulation rate for three age groups are shown in Figure 4. The age groups shown in Figure 4 were separated by commonly used categorical age limits. Thus, the YCI group represented the 10 participants who were ≤ 45 years of age; the MCI group represented the 10 participants who were between 46-64 years of age; the OCI group represented the 10 participants who were ≥ 65 years of age. Although the average group data plotted in Figure 4 showed age effects, there was extensive within-group variability in GDTs. Thus, the effect of age was not statistically significant when participants were divided into traditional age groups. The results of the final LME model, which applied standardized values for age as a continuous variable (with no categorical age groups), are shown in Table 2.

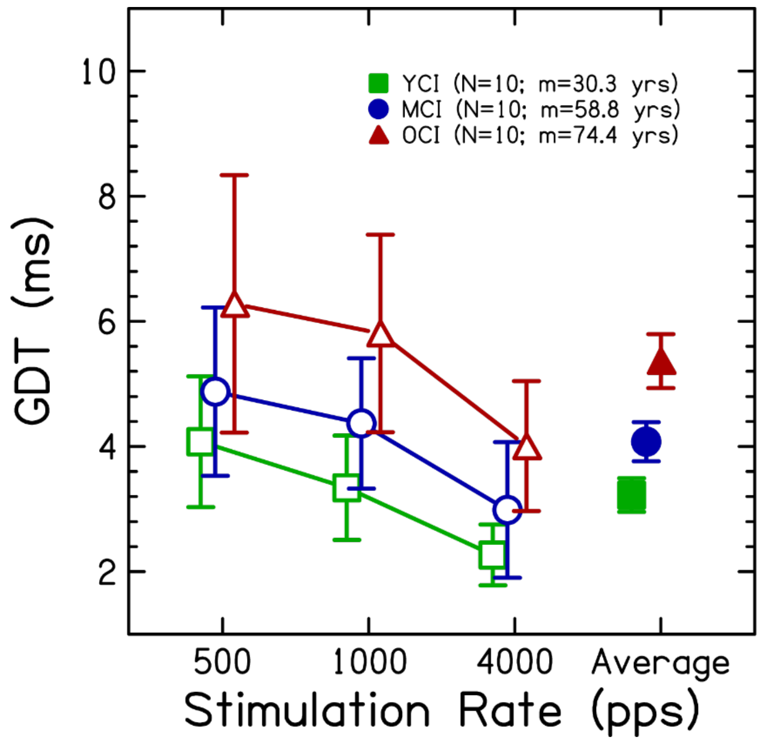


Figure 4. GDTs for each age group plotted as a function of electrical stimulation rate. YCI group = green squares. MCI = blue circles. OCI = red triangles. Filled symbols represent group averages across all stimulation rates. Error bars = ±1 standard error.

The average GDT (intercept coefficient) was 3.99 ms, which represents the average threshold measured at the reference stimulation rate of 1000 pps, for a participant with an average ECAP slope and an average age (54.3 years). There was a significant main effect of stimulation rate on GDTs. Compared to the reference rate (1000 pps), GDTs measured at 500 pps significantly increased (worsened) by 0.87 ms (p<0.001). When measured at 4000 pps, GDTs significantly decreased (improved) by 1.03 ms compared to the reference rate (p<0.001). This pattern suggests a significant improvement in GDTs with increasing stimulation rate. There was also a significant main effect of ECAP slope. On average, with every 1 SD increase in ECAP slope, GDTs decreased (improved) significantly by 1.02 ms (p=0.03) at the reference rate. Thus, electrodes that exhibited steeper ECAP AGFs had generally better GDTs.

Table 2.
Final LME Model for GDTs.

Fixed effects	**Coefficient**	***SE***	***t***	***p***
Intercept	**3.99**	**0.57**	**6.94**	**<0.001**
Rate (**0 = 1000 pps reference**):				
(-1 = 500 pps)	**0.87**	**0.17**	**5.17**	**<0.001**
(1 = 4000 pps)	**-1.03**	**0.17**	**-6.10**	**<0.001**
Age (standardized)	0.66	0.57	1.17	0.25
ECAP (standardized)	**-1.02**	**0.48**	**-2.15**	**0.03**
Interactions				
Rate 500 pps × Age	-0.03	0.16	-0.16	0.87
Rate 4000 pps × Age	0.16	0.16	0.97	0.33
Rate 500 pps × ECAP	**0.46**	**0.22**	**2.14**	**0.03**
Rate 4000 pps × ECAP	**1.24**	**0.22**	**5.71**	**<0.001**
ECAP × Age	-0.28	0.36	-0.79	0.43
Rate 500 pps × ECAP × Age	**0.38**	**0.15**	**2.55**	**0.01**
Rate 4000 pps × ECAP × Age	**0.48**	**0.15**	**3.14**	**0.001**
Random effects	**Variance**			***SD***
Subject (intercept)	7.12			2.67
Subject/Electrode (intercept)	4.11			2.03
Residual	4.01			2.00

Note. All values are expressed in ms.

Significant two-way interactions were also identified between stimulation rate and ECAP slopes. These interactions suggested that although steeper ECAP slopes predicted better GDTs at the reference rate of 1000 pps, this effect was somewhat offset at 500 and 4000 pps. GDTs measured at an electrode with a steep ECAP slope (+1 SD above the mean) increased significantly (worsened) by 0.46 ms at 500 pps compared to the reference rate (p=0.03). Similarly, GDTs obtained from an electrode with a steep ECAP increased significantly by 1.24 ms at 4000 pps compared to the reference rate (p<0.001). The interaction between

ECAPs and 4000 pps, specifically, predicts that the benefit received from a steep ECAP slope at the reference rate would be completely eliminated, and even reversed, when using a 4000 pps signal. The model predicted that at 4000 pps, GDTs would be slightly worse (0.2 ms) at an electrode with a steep ECAP slope compared to an average ECAP slope value.

There were also significant three-way interactions of 500 pps × ECAP × Age and 4000 pps × ECAP × Age. These interactions are highlighted in Figure 5 (panel I), which displays linear regression lines for each rate × age combination in order to easily visualize the relationships between GDTs and ECAPs in each condition (note, however, that a linear regression was not used for data analysis). Raw data points for each electrode from each participant are also plotted. These three-way interactions suggested that the benefit received from a steep ECAP slope is not only offset or eliminated by changes in rate, but it is further dampened by an increase in chronological age. GDTs at 500 pps at an electrode with a steep ECAP slope were significantly worsened by 0.38 ms when chronological age was increased by 1 SD above the mean (+19.1 years), compared to a participant with the average age of 54.3 years (p=0.01). Similarly, GDTs at 4000 pps with steep ECAP slopes were significantly worsened by 0.48 ms with a 1 SD increase in chronological age compared to the average age (p=0.001). This suggested that the reversal from a *benefit* from a steep ECAP slope on GDTs to a slight *disadvantage* from a steep ECAP slope at 4000 pps, as described above, would persist and increase in size with older participants.

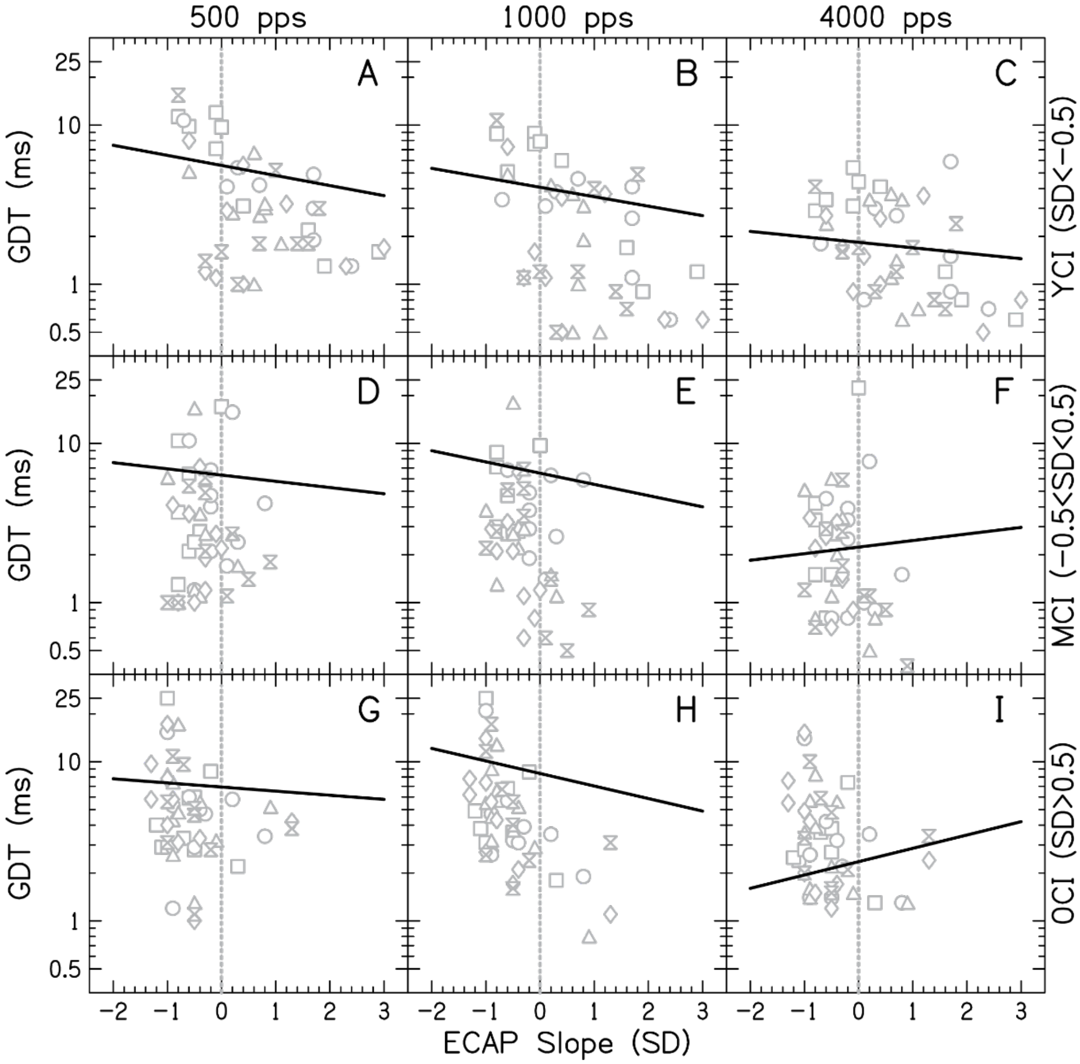


Figure 5. GDTs plotted as a function of ECAP slope for the three stimulation rate conditions (columns). Participants were separated into three age groups in order to highlight the interactions between rate, ECAP slope, and chronological age. YCI group (N=9) represents participants with ages ≤-0.5 SD below the mean (≤44 years). MCI group (N=11) represents participants with ages between -0.5-0.5 SD around the mean (45-63 years). OCI group (N=10) represents participants with ages >0.5 SD above the mean (≥64 years). Note: GDTs are plotted on a logarithmic scale to compensate for the majority of thresholds falling below 10 ms and for a limited number of outliers whose GDTs fell above 15 ms. See Appendix A for a similar figure containing the same data plotted on a linear scale.

It is clear from Figure 5 that most of the participants who showed steep ECAP slopes (values >0 on the x-axis) belonged to the YCI group. Figure 6 shows the frequency distribution of standardized ECAP slopes for the three age groups that were designated in Figure 5. There was substantial overlap in ECAP slope values across the MCI and the OCI groups, with the majority of those values falling below the mean. The YCI group, however, has a much larger range of slope values, with the majority falling above the mean. The YCI group also had eight instances in which the slope was ≥ 2 SD above the mean. The proportion of ECAP slopes falling *above* zero in each group were: 75.5% for YCI, 26.1% for MCI, and only 12.5% for OCI.

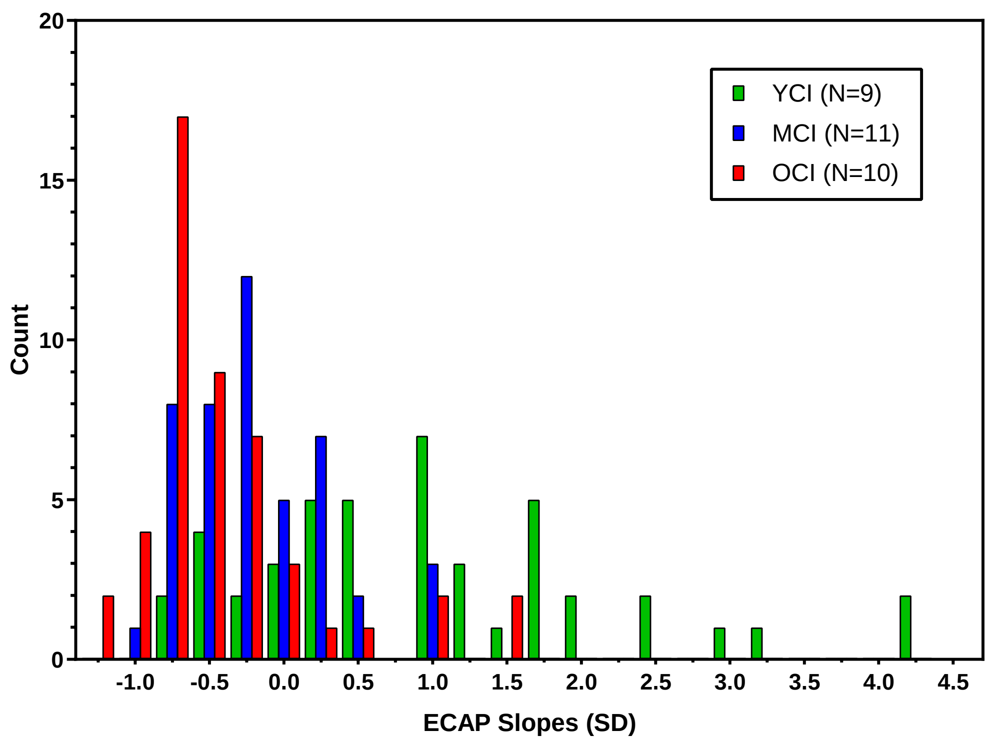


Figure 6. Frequency distributions of standardized ECAP slope values for the nine YCI participants (green bars), 11 MCI participants (blue bars), and 10 OCI participants (red bars). ECAP slopes with a value of 0 represent the mean ECAP slope for this group of participants. Bin width is 0.25 SD.

Electrode location.

Average GDTs at each electrode location for the three stimulation rates are shown in Figure 7. Two-tailed, paired-samples t-tests (with Bonferroni corrections) were used to compare average GDTs between every two electrode locations to determine if there was a consistent effect of electrode location across all participants. There was a significant difference between results for E4 (most basal electrode) (M=5.7 ms, SD=5.2) and E8 (M=4.1, SD=3.1); $t(28)=3.6$, $p=0.001$, suggesting that average GDTs were significantly higher (worse) for E4 when compared to E8. The difference between E4 and E16 was similar to the E4 - E8 comparison, but did not reach significance with the more conservative alpha level determined by the Bonferroni correction. No other differences between electrodes were found to be significant.

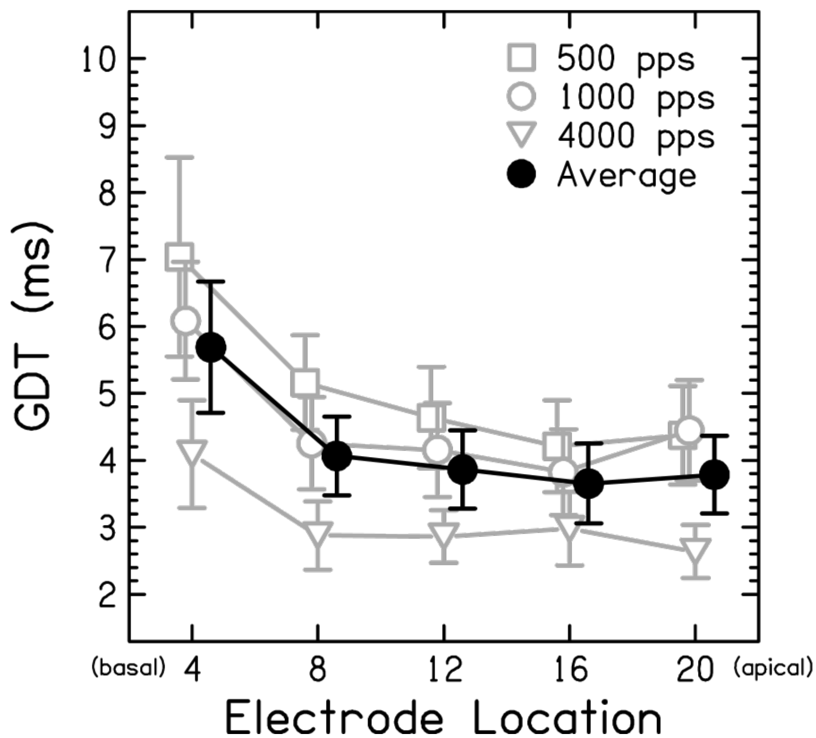


Figure 7. Average GDTs for all participants in each stimulation rate condition for each electrode location. Squares = 500 pps. Open circles = 1000 pps. Triangles = 4000 pps. Filled circles = average GDTs across all stimulation rate conditions. Error bars = ±1 standard error.

One factor that could have contributed to this pattern of results was the presentation level (MCL) that was chosen by the participants, as the levels varied across electrode locations. In particular, the level for E4 was often set either substantially above or below the average presentation level for the other four more apical electrode locations. In order to determine if systematic differences in stimulus presentation level contributed to this pattern, a correlation matrix was constructed to evaluate pair-wise correlations between the presentation level and GDTs for each electrode location at each stimulation rate. Presentation levels were normalized for each participant so that each level represented the difference between the absolute presentation level and that participant’s average level established for that stimulation rate. Figure 8 shows the correlation matrix for all pair-wise correlations between GDT and normalized presentation level. There were no significant correlations for any rate × electrode combination, suggesting that the presentation level relative to the average level used for each participant was not correlated with GDTs.

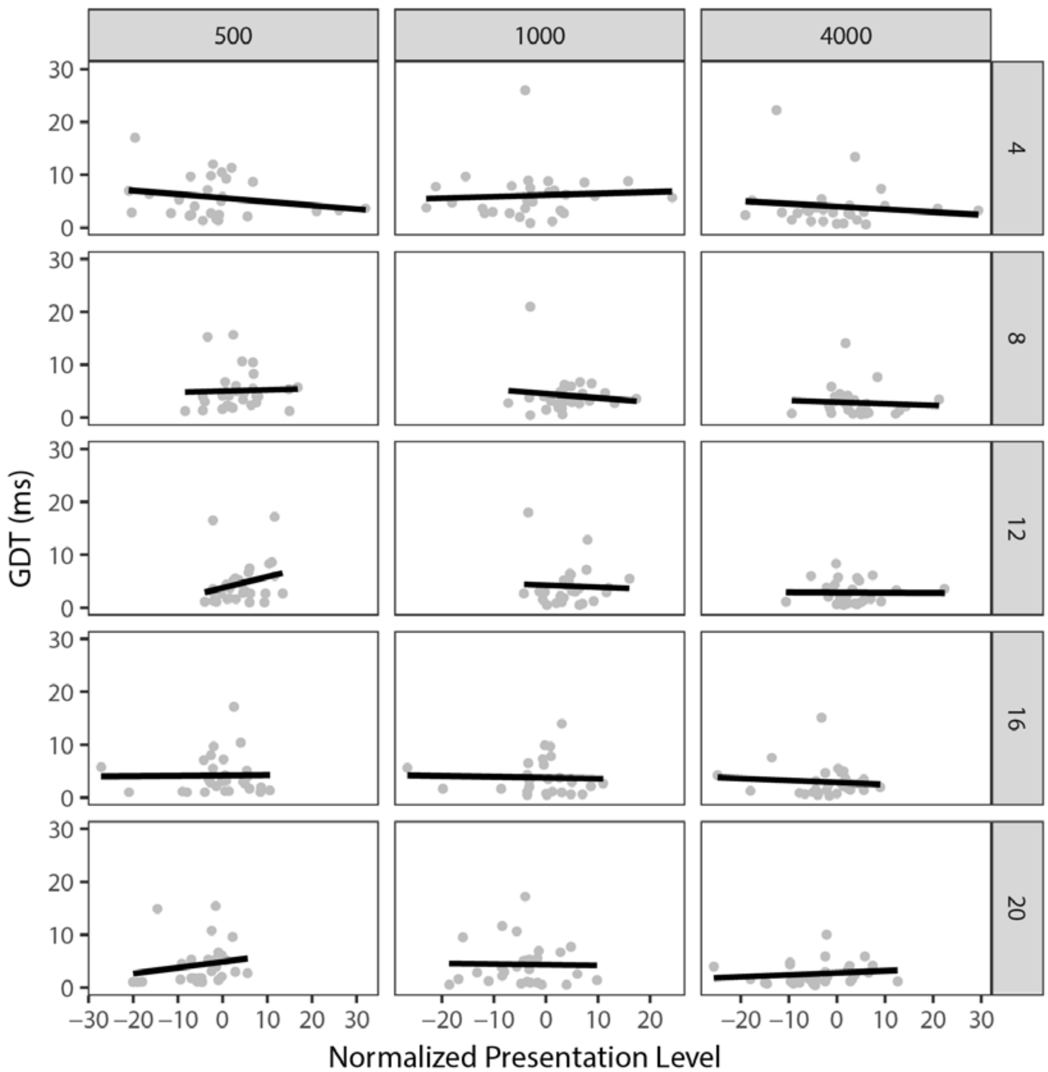


Figure 8. Correlation matrix for pair-wise comparisons between normalized presentation levels and GDTs for each electrode location (rows) using each stimulation rate (columns).

Discussion

This study investigated the relative contributions of chronological age and peripheral neural survival (as measured by ECAP slope) to gap detection ability measured at different electrical stimulation rates in adult CI users. The average GDT obtained from this group of CI users was 3.9 ms. This result is within the range of GDTs that could be expected from a group of acoustic-hearing listeners with a similar range of ages (Plomp, 1964; Schneider et al., 1994), as well as from a group of CI users (Shannon, 1989). Participants with electrodes that exhibited steeper ECAP slopes had better GDTs in general, but this effect was reduced at some stimulation rates. The advantage associated with steeper ECAP slopes was further diminished with advancing age. The results of this study suggest that there are both peripheral and central contributions to gap detection ability in CI users. The contribution of chronological age above and beyond the contribution of peripheral neural survival remains unclear due to an apparent decline in ECAP slope concomitant with advancing age.

Signal-related factors: Electrode location and stimulation rate.

As expected, GDTs varied across electrode locations within individuals, and the pattern of results was not consistent across participants. This result is consistent with previous studies that measured GDTs at multiple electrode locations along the array (Bierer et al., 2015; Garadat & Pfingst, 2011), suggesting a variation in temporal processing ability at different cochlear positions within the same CI user. The current results, however, revealed that GDTs obtained from the most basal electrode (E4) were higher (worse) compared to the other more apical electrodes (Figure 7, p. 38). Measurements obtained from basal electrodes are notoriously unpredictable and often relatively poor compared to other electrode locations in the context of single-electrode psychoacoustic experiments (e.g., McDermott & McKay, 1994). Clinical mapping procedures for establishing comfortable loudness levels for basal electrodes can also be challenging. The nature of surgical insertion angles and the shape of both perimodiolar and straight electrode arrays typically results in a larger electrode-to-modiolus distance for basal electrodes compared to apical electrodes (van der Beek, Briaire, van der Marel, Verbist, & Frijns, 2016). Additionally, SGC degeneration in individuals with hearing loss is more severe in the basal half of the cochlea (Zimmermann, Burgess, & Nadol Jr, 1995). Variables such as these, which may be specific to the basal portion of the cochlea, could result in poorer GDTs, either because of relatively poor peripheral neural survival in that location, or because of potentially questionable MCLs that were established during mapping. Many participants expressed their dislike for listening to single-electrode stimulation at E4, which they described as very high-pitched. In some cases, participants' MCL for E4 was substantially lower than the other four electrode locations, but this was not always the case as some participants' MCL for E4 was set higher than the other electrodes. A *post hoc* analysis of the effect of presentation level did not reveal a significant relationship between level and GDTs (Figure 8, p. 39).

Results showed a significant improvement in GDTs with increasing the stimulation rate (Figure 4 and Table 2, pp. 32-33). On average, GDTs improved by nearly 2 ms using a 4000 pps signal compared to a 500 pps signal. A primary difference between high- and low-rate electrical stimulation is the IPI, which defines the time interval between individual biphasic pulses. For lower stimulation rates (i.e., 500 pps), the IPI is longer compared to higher rates (i.e., 4000 pps). At 500 pps, the IPI is 2 ms. At 4000 pps, the IPI is reduced to only 0.25 ms. The presence of a longer IPI could introduce a level of uncertainty for discriminating a short temporal gap inserted into an otherwise continuous pulse train from the intervals between consecutive pulses. Shorter IPIs could also contribute to a "smoother" percept for pulsatile stimulation rather than a "rough" percept with longer IPIs (Busby & Clark, 1999), resulting in a more salient gap. This result is somewhat inconsistent with previous psychoacoustic studies that evaluated the effect of electrical stimulation rate on gap detection ability. Busby and Clark (1999) measured GDTs in a group of prelingually deafened CI users to investigate the effects of signal-related factors, including stimulation rate, and listener-related factors, including DoD and duration of CI use. On the group level, there was no significant effect of stimulation rate on GDTs; however, two out of the 15 participants tested showed significant improvements at the highest stimulation rate of 1000 pps compared to the lower rates (200 and 500 pps). In the current study, GDTs significantly decreased with each increase in stimulation rate (from 500 to 1000 pps, and from 1000 to 4000 pps). Therefore, it is possible that stimulation rate could have impacted results in the Busby and Clark study if a higher rate (i.e., 4000 pps) was tested, or if more participants were included in their data set. Additionally, participants in the Busby and Clark study were recruited based on onset of hearing loss to include only implantees with prelingual hearing loss. The current study, however, recruited participants based on chronological age. As a result, participants in the Busby and Clark study were young adults and adolescents between the ages of 10-21 years of age who were implanted as children. This creates potential confounds in participants' etiologies and age at implantation in comparison to the current study, which recruited participants with a variety of ages at which hearing loss was acquired.

Alternatively, it was hypothesized that age differences in GDTs would be largest at faster stimulation rates because of age-related alterations in the temporal discharge patterns of SGCs (e.g., refractory limitations). This hypothesis was somewhat supported, although the interaction between age and rate was not significant, age and rate did significantly interact within the context of ECAP slope (Figure 5, p. 35). Thus, the effect of the signal-related factor of stimulation rate significantly interacted with both listener-related factors of chronological age and ECAP slope.

Listener-related factors: Age and ECAP slope.

Chronological age and ECAP AGF slope were identified as the two listener-related factors that significantly predicted GDTs in this group of CI users (Table 2, p. 33). In general, steeper (higher) ECAP slope values were associated with better GDTs. On average, GDTs improved by 1 ms for electrodes with ECAP slopes falling 1 SD above the mean slope compared to electrodes that obtained average ECAP slopes. Apart from the effect of stimulation rate, ECAP slope was the strongest predictor of GDTs. However, the effects of stimulation rate and ECAP slope significantly interacted with the chronological age of the listener.

Results revealed significant three-way interactions between 500 pps × ECAP × Age and 4000 pps × ECAP × Age. Although steep ECAP slopes predicted improved GDTs at the reference rate of 1000 pps for participants of an average age, this benefit was offset slightly at 500 pps and was essentially eliminated at 4000 pps. When age was considered, increases in age further diminished the advantage obtained from having steep ECAP slopes. In particular, the statistical model predicted that steeper ECAP slopes put an older listener at a disadvantage at 4000 pps compared to having a relatively shallow ECAP slope. In other words, at 500 and 1000 pps stimulation rates, shallow ECAP slopes hurt gap detection performance. At a 4000 pps rate, however, having a shallow ECAP did not impact performance for a younger participant, but there was the opposite result for an average-aged and an older participant. Thus, advancing age was associated with a reversal in the ECAP benefit for the 4000 pps stimulation rate condition. Predicted data for individuals falling into each age group with different ECAP slopes is plotted in Figure 9.

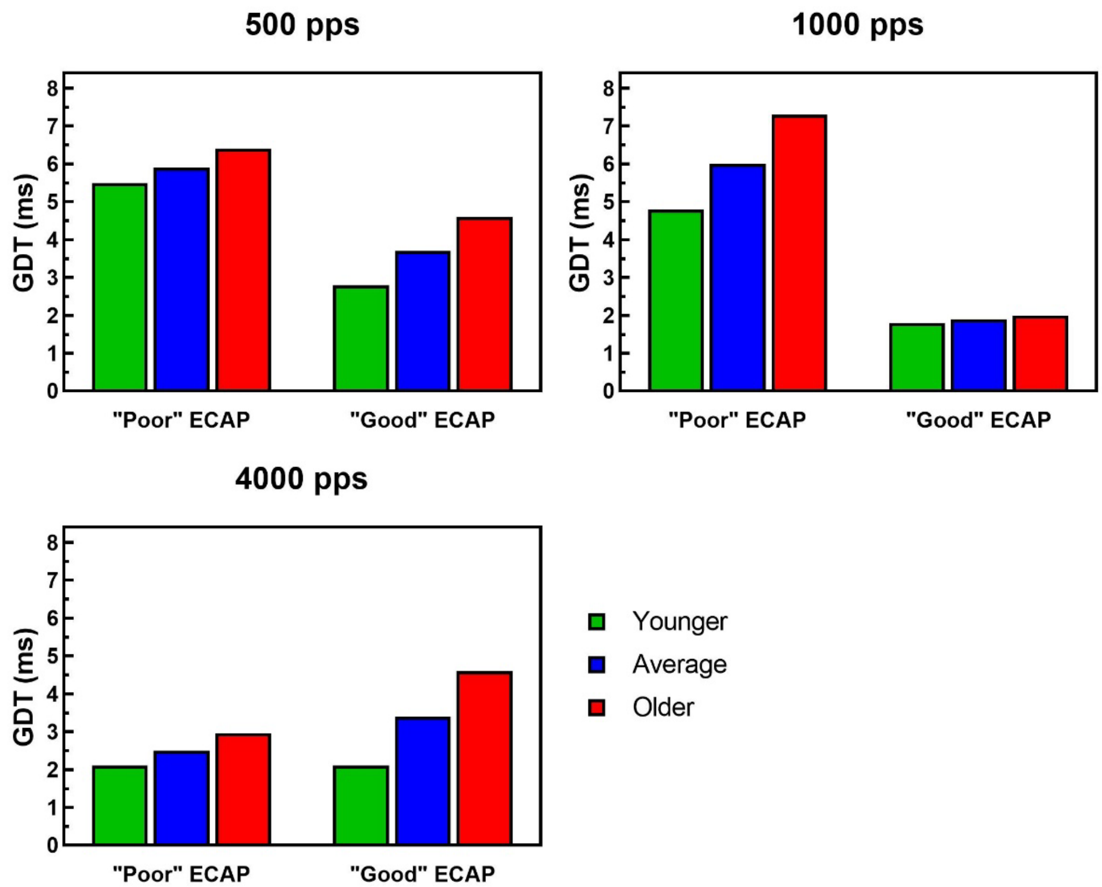


Figure 9. Model predictions for three hypothetical participants: one younger participant with an age equal to 1 SD below the mean age (35-year-old), one average-age person (54-year-old), and one older participant with an age equal to 1 SD above the mean age (73-year-old). Predicted GDTs are plotted for each age and ECAP combination. “Poor” ECAPs were defined as a slope value equal to 1 SD below the mean. “Good” ECAPs were defined as a slope equal to 1 SD above the mean.

The reversal of the ECAP benefit at 4000 pps for older listeners could be caused by a limited number of samples of older participants with steep ECAP slopes. Figure 6 (p. 36) showed the frequency distribution of ECAP slope data when participants were divided into three separate age groups. Over 75% of the ECAP slopes collected from YCI participants fell above zero (the mean ECAP slope for all participants), whereas only 12.5% of OCI participants had ECAP slopes that fell above the mean. This result supported the hypothesis that older participants would have shallower ECAP slopes compared to younger participants, presumably because of an age-related reduction in SGCs. The limited range of ECAP slopes obtained from older and middle-aged participants precluded a thorough analysis of chronological age *per se* as a “central” contribution vs ECAP slope as a “peripheral” contribution. However, the limited range of ECAPs in the two older groups is evidence in and of itself that the process of aging impacts the peripheral auditory system in CI users. The data also suggest that this age-related decline in peripheral neural survival co-occurs with a decline in central auditory temporal processing abilities for the detection of silent gaps. Thus, the possibility that there is a central contribution of age above and beyond any peripheral contribution remains. This finding is consistent with data from acoustic-hearing listeners and from animal models (Walton, Frisina, & O'Neill, 1998).

A similar experiment conducted by Mussoi and Brown (2019) measured GDTs in one younger group (N=10; mean age = 27.8 years; range = 18 to 40 years) and one older group (N=10; mean age = 74.8 years; range = 68 to 82 years) of CI participants. Unlike the current study, the groups were matched for the DoD prior to implantation. Peripheral changes in temporal processing were evaluated with ECAP recovery functions following a single biphasic pulse as well as following a constant-amplitude pulse train. Mussoi and Brown did not find a significant effect of age on GDTs. The only metric that revealed an age effect was the ECAP recovery functions following a pulse train masker, indicating that older CI participants had longer neural recovery times compared to younger participants. This result is similar to the current study in that a main effect of peripheral status (ECAP) was significant while the effect of age was only significant within the context of stimulation rate and ECAPs. Additional differences in the experimental design and statistical analyses between the Mussoi and Brown study and the current study may have contributed to different conclusions. Mussoi and Brown (2019) recruited two distinct groups of participants, which designated age as a categorical variable. Additionally, all measurements were obtained from a single, mid-array electrode at a single stimulation rate of 400 pps. Thus, their study design did not allow for more robust statistical analyses that could identify higher-order interactions between age, GDTs, and ECAP recovery functions.

The effect of chronological age on CI outcomes is often confounded by differences in the age at onset of hearing loss and the etiology of deafness between age groups. Younger CI participants tend to have earlier onsets of hearing loss and are more likely to have hearing loss with a genetic component. A larger sample of participants would be required to conduct a thorough investigation of the impact of age that is independent from onset and etiology confounds. In addition, ECAP input-output functions (AGFs) are just one of many ECAP measurements. Peripheral status can also be estimated by other types of ECAP assessments, including recovery functions, spread of excitation, and rate adaptation. The use of a different metric for estimating peripheral neural survival, either by a different ECAP assessment or using imaging techniques (e.g., CT scans), may be more sensitive and could expand the range of responses from an older group.

Conclusions

This study evaluated the effect of age on gap detection ability at a variety of electrical stimulation rates. It was hypothesized that results would show a general age-related decline in central temporal processing ability. Age-related changes in peripheral neural survival were also expected to contribute to the results for behavioral measures of central temporal processing. Peripheral status, as measured by ECAP AGF slopes, significantly contributed to gap detection ability in general, with steeper slopes predicting better GDTs. When a signal-related factor (stimulation rate) and an additional listener-related factor (age) were also considered, all three factors significantly predicted gap detection ability. Specifically, advancing age was associated with a reversal in the predictions regarding peripheral status. It was hypothesized that steeper ECAP slopes would be associated with better gap detection ability in general. However, the results showed that steeper ECAP slopes predicted poorer gap detection ability at 4000 pps in older participants. This result is likely due to a limited range of ECAP (mostly shallow) slopes obtained from older participants. The apparent negative impact of age on peripheral auditory status limited the evaluation of the independent contributions from *central* aging and *peripheral* aging on auditory temporal processing ability for detecting silent gaps. This is an important area for future research with the objective of quantifying the relative contributions of central vs peripheral factors in auditory aging.

Study 2: Effect of Age on Amplitude Modulation Detection in CI Users

Introduction

Another measure of auditory temporal processing ability is amplitude-modulation (AM) detection. Although AM detection is considered a basic psychophysical measure of auditory temporal processing, AM signals are dynamic and are more similar to speech than signals used in gap detection tasks. AM detection threshold (MDT) refers to the smallest depth of modulation that can be detected. MDTs are typically measured at multiple envelope modulation rates/frequencies and the resulting function is known as a temporal modulation transfer function (TMTF). AM detection, and temporal envelope processing in general, are of particular importance to CI users' perception of speech signals because CI speech processing is characterized by a reduction in spectral resolution and temporal fine structure, while the temporal envelope remains intact (Shannon et al., 1995). There is an age-related decline in the ability to process temporal envelope cues as observed in animal models (Walton, Simon, & Frisina, 2002) and in humans (Grose, Mamo, & Hall, 2009; Leigh-Paffenroth & Fowler, 2006; Purcell et al., 2004). Thus, older CI users are at a potential disadvantage for perceiving speech via a CI.

Temporal cues can be characterized based on their frequency range. Rosen (1992) defined three ranges of modulation frequencies/rates, which transmit different speech cues: (1) Envelope, defined as fluctuations in amplitude below 50 Hz, which is primarily related to jaw and articulator movement; (2) Periodicity, defined as rates between 50 and 500 Hz, which convey information relating to fundamental vocal-fold vibration frequency (f0); and (3) Fine structure, defined as rates >600 Hz, which represent harmonic structure of the signal as well as noise-like sounds produced by turbulent airflow in the vocal tract (e.g., fricative consonants). Cues from the slow-moving envelope fluctuations are considered the primary cues needed for speech perception (Shannon et al., 1995); however, slightly faster fluctuations that transmit periodicity information may convey important f0 cues for identifying a talker in the presence of background noise (Qin & Oxenham, 2005).

AM detection ability in acoustic-hearing listeners.

Signal-related factors.

In general, AM detection ability declines with increasing modulation frequency (e.g., Bacon & Viemeister, 1985), but the shape of the TMTF is affected by both signal- and listener-related factors. The choice of carrier signal can drastically change the shape of the TMTF. When measured with a broadband noise carrier, MDTs in normal-hearing listeners follow a low-pass filter characteristic and worsen in a monotonic fashion as the rate of modulation increases past a transition (or cutoff) frequency between 50-100 Hz (Bacon & Viemeister, 1985; Houtgast, 1989). The theoretical basis for this TMTF shape is attributed to the sliding temporal integrator (Moore et al., 1988), similar to the concept of gap detection described earlier, in which rapid temporal changes are not internally represented as well as slower temporal changes (see Figure 1 panels D and E, p. 15).

When measured using sinusoidal carriers, however, the TMTF demonstrates a non-monotonic function (Kohlrausch, Fassel, & Dau, 2000). Modulation of sine tones results in the generation of spectral sidebands, which can cue the listener to the presence of AM. When sidebands are the only spectral energy to fall into a signal auditory filter (i.e., the sidebands are resolved), an alternative cue to aid in AM detection is introduced to acoustic-hearing listeners. Once the AM rate exceeds the frequency that would result in resolvable sidebands, MDTs will decrease (improve). This results in non-monotonic TMTFs that vary in shape depending on the carrier frequency. TMTFs measured with low-frequency carriers (<1000 Hz) will show decreases in MDT with relatively slow AM rates because the auditory filter bandwidth is narrower at low frequencies, allowing sidebands to be resolved even when positioned close to the carrier (center) frequency (Moore & Glasberg, 1983). For high-frequency carriers (>3000 Hz), decreases in MDT are not apparent until after the AM rate is ≥500 Hz because the auditory filter bandwidth is much wider and requires sideband components to fall outside the critical bandwidth in order to be resolved (Kohlrausch et al., 2000).

Narrowband noise carriers result in different TMTF shapes depending on the bandwidth of the signal. MDTs are sensitive to the inherent AM fluctuations in the narrowband noise carrier itself. The average envelope fluctuation rate within a noise carrier is approximately 64% of the bandwidth of the stimulus (Rice, 1944). Noise carriers with narrow bandwidths, which are composed of inherent low-frequency amplitude fluctuations, result in poorer MDTs at low AM rates.

Noise carriers with wide bandwidths, which are composed of high-frequency amplitude fluctuations, result in poorer MDTs at high AM rates. In effect, the random fluctuations in the noise carrier itself can interfere with the AM imposed on that signal. This result is typically accounted for based on the concept of a modulation filter bank within the central auditory system (Kay, 1982). A modulation filter bank is an array of neurons that are thought to be tuned to respond to specific modulation frequencies; a single neuron essentially acts as a filter in the temporal modulation domain. Candidate neurons with the appropriate response properties for a modulation filter bank have been identified in the central auditory pathway (Lorenzi, Micheyl, & Berthommier, 1995; Møller, 1976; Rees & Møller, 1983).

Listener-related factors.

The shape of the TMTF is impacted by listener-related variables in acoustic-hearing listeners, including hearing sensitivity and age. AM detection in normal-hearing listeners is best at low modulation frequencies below a transition frequency of 50 Hz with thresholds at approximately -25 dB (re:20 log[*m*]) (Bacon & Viemeister, 1985; Viemeister, 1979). Older listeners with high-frequency hearing loss show abnormal TMTF characteristics, with poorer AM detection thresholds overall and a lower transition frequency, after which detection thresholds worsen at a faster rate with increasing modulation frequency compared to younger, normal-hearing listeners (Bacon & Viemeister, 1985). However, in at least one study that accounted for the effect of high-frequency hearing loss, the effect of age alone did not result in poorer AM detection ability for a broadband noise carrier (Takahashi & Bacon, 1992). Conversely, AM detection ability using sine-tone carriers showed an effect of age, which was independent of hearing sensitivity. He et al. (2008) measured TMTFs using 500 Hz and 4000 Hz sine-tone carriers in younger and older listeners with normal hearing sensitivity. Significant age-related differences in AM detection were observed when performance was dependent on primarily temporal cues. Age-related differences in AM detection above the transition frequency were larger for the 500-Hz carrier, where performance was still somewhat dependent on temporal cues, compared to the 4000-Hz carrier. These results suggested a general decline in the synchronization of neural responses to temporal envelope fluctuations with advancing age.

AM detection ability in CI users.

Signal-related factors.

Some studies have shown that TMTF characteristics for CI users closely resemble those of normal-hearing, acoustic listeners (Busby, Tong, & Clark, 1993; Fraser & McKay, 2012; Shannon, 1992). Other studies have shown quite different results, with CI users having steeper TMTF slopes and lower cutoff frequencies compared to normal-hearing listeners (e.g., Park, Won, Horn, & Rubinstein, 2015). Methodological differences between studies, including whether direct stimulation or acoustic presentation was used, may have impacted results. Direct stimulation bypasses any sound-processor related variables that may differ between participants and may differentially modify the input signals (e.g., automatic gain control [AGC], real-time peak-picking strategies, noise reduction algorithms processing strategy, and microphone directionality). Thus, differences in the stimulus presentation techniques may have contributed to the mixed results observed for normal-hearing vs CI users in AM detection studies.

It is also important to note the differences in presentation of acoustic signals to normal-hearing listeners and electrical signals to CI users via direct stimulation. Acoustic hearing allows access to many cues that are not available to listeners with electric hearing (e.g., spectral sidebands). CIs bypass the cochlear structures responsible for the acoustic filtering (i.e., basilar membrane filtering) and transduction of sound, and stimulate the auditory nerve directly. The anatomic and physiologic characteristics of the peripheral auditory system that contribute to the perception of loudness are not available to CI users (e.g., excitation patterns, phase locking, nonlinear compressive mechanics). Spectral information via a CI is also different than in acoustic hearing; spectral cues are conveyed by the tonotopic electrode location. Temporal information is limited to the envelope modulations within the signal, because the temporal fine structure is removed. Therefore, many of the peripheral processes, including auditory filter bandwidths, which underlie the various TMTF shapes when presented with different acoustic stimuli are almost completely removed in electric hearing.

The signal-related factors that impact AM detection in CI users include presentation level, electrical stimulation rate, and electrode location. AM detection tends to worsen with decreasing presentation level (Galvin & Fu, 2005; Pfingst, Xu, & Thompson, 2007), but the magnitude of this level effect varies greatly between listeners. Slower electrical carrier rates, or stimulation rates, tend to produce better AM detection thresholds (Galvin & Fu, 2005, 2009; Pfingst et al., 2007). This is not to say that smaller electrical dynamic ranges, which occur with slower stimulation rates, are associated with better AM detection. Pfingst et al. (2007) compared CI participants' mean MDTs to their dynamic ranges, and although their results demonstrated better MDTs with lower stimulation rates, there were positive correlations between MDTs and dynamic range. This result suggested that participants with larger dynamic ranges had better MDTs. Additionally, the effect of stimulation rate on MDTs is highly variable between CI listeners, which suggests that listener-related or other biological variables may be a factor.

Finally, MDTs have been shown to vary across different electrode locations within a single CI user (Garadat, Zwolan, & Pfingst, 2012; Pfingst et al., 2007). Cochlear pathology, and the resulting survival of SGCs, are highly variable along the length of the cochlea as well as between individuals (Hinojosa & Marion, 1983; Khan, Whiten, Nadol Jr, & Eddington, 2005). Differences in the neural survival pattern at each electrode location may underlie these across-electrode differences in MDTs. To summarize, although there are typical patterns of MDTs obtained from CI users in response to changing signal-related factors, there remains a large amount of individual variability. The variability in results across participants suggests that listener-related factors may contribute to CI users' AM detection ability.

Listener-related factors.

While AM detection ability 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, Pelizzone, Saudan, & Boex, 1994; 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 in CIs also tend to have relatively small sample sizes and little consideration of participants' chronological age, age at onset of hearing loss, and degree of neural survival. Additionally, many previous studies only measured MDTs 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 because local neural survival has been shown to contribute to single-electrode AM detection ability in CI users, with poorer MDTs associated with poorer peripheral neural survival estimates (Garadat et al., 2012; Garadat, Zwolan, & Pfingst, 2013). 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). 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 on temporal envelope modulations to understand speech. These consequences of reduced temporal processing could be the underlying source of OCI users' speech recognition limitations.

Summary and hypotheses.

The goal of Study 2 was to identify the effect of age on AM detection ability at different electrical stimulation rates. The contribution of other age-related factors (peripheral neural survival) to participants' performance on the AM detection task was also estimated. Based on the results from studies that tested younger and older normal-hearing listeners, it was hypothesized that OCI users would require larger depths of modulation compared to YCI and MCI 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 fast electrical stimulation rates, because of the altered temporal discharge patterns associated with age-related SGC degeneration. Older CI users show improved speech recognition when presented with a relatively slow electrical stimulation rate of 500 pps (Shader *et al*., under review). Therefore, this low-rate advantage may also be reflected in participants' AM detection ability. OCI participants were also expected to have shallow ECAP AGF slopes compared to YCI and MCI participants due to age-related reductions in SGCs. A limited number of SGCs would imply that there is a reduced number of neurons available to encode electrical signals, which could result in poor temporal envelope encoding (Lopez-Poveda, 2014).

Method

Participants.

Twenty two participants were recruited to represent a wide range of ages from 23-84 years (mean = 56.1 ± 18 years) with at least two participants' ages falling in each decade. Individuals who participated in Study 1 were also eligible to participate in Study 2, therefore, some participants were included in both Study 1 and Study 2. All participants passed a cognitive screening for dementia with a score of ≥22 on the Montreal Cognitive Assessment (MoCA) (Nasreddine et al., 2005). As described in Study 1, a MoCA score of 22-25 indicates that an individual is at risk for mild cognitive impairment (Cecato et al., 2016), but these individuals were not excluded from participating in the experiment. All participants were implanted with Cochlear-brand devices, primarily with perimodiolar electrode arrays, which are intended to sit in close proximity to spiral ganglion nerve fibers, and make electrophysiological measurements more feasible. Participant demographics are provided in Table 3. Electrophysiology was used to estimate each participant's degree of neural survival. All participants were required to have at least one year of CI experience to ensure stable responses and tolerance to electrical signals (Hughes et al., 2001).

Table 3.
Participant Demographics Table: Study 2.

Participant	Age	Gender	Age at HL Onset	DoD	Etiology	Device
CDE	23	M	0	12	Connexin 26	CI24RE(CA)
CAR	25	M	4	14	Hereditary	CI24RE(CA)
CDA	27	F	0	20	Connexin 26	CI512(CA)
CAT	30	M	10	9	Hereditary	CI24RE(CA)
CBP	37	F	5	15	Hereditary	CI24M
CCS	41	M	1	37	Meningitis	CI422
CBW	45	M	26	5	COGAN Syndrome	CI24R(CS)
CAP	50	F	38	1	Hereditary	CI24RE(CA)
CDR	50	F	3	44	Unknown	CI24RE(CA)
CAS	54	F	41	3	Hereditary	CI24RE(CA)
CDY	54	F	40	7	Endocarditis	CI512(CA)
CBF	59	M	5	47	Hereditary	CI24RE(CA)
CBG	64	F	4	53	Rh Incompatibility	CI512(CA)
CBR	65	F	0	57	Unknown	CI24RE(CA)
CAJ	65	F	0	47	Unknown	CI24M
CCR	69	F	2	60	Measles	CI24RE(CA)
CAF	71	F	5	49	Unknown	CI24RE(CA)
CBT	75	F	50	20	Unknown	CI24RE(CA)
CCA	76	M	70	1	Ototoxicity	CI512(CA)
CBC	81	F	35	41	Unknown	CI24RE(CA)
CBB	83	M	77	2	Aging	CI24RE(CA)
CCX	84	M	62	12	Noise Induced	CI24RE(CA)

Note. HL=hearing loss; DoD=duration of deafness.

Mapping.

Each participant’s electrical dynamic range (DR) was measured by establishing threshold and maximum comfortable levels using standard CI mapping procedures for each test electrode for every stimulation rate. Threshold (“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. Maximum comfortable (“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.

All stimulus presentation was performed using direct stimulation of the electrode array with the Nucleus Implant Communicator (NIC2) and a L34 research sound processor. Stimuli were 500-ms AM pulse trains with a 25-µs phase duration and an 8-µs interphase gap. Monopolar stimulation was used. Stimuli were amplitude modulated using seven modulation depths: 1, 3, 5, 10, 25, 50, and 100%, at three modulation frequencies: 50, 100, and 250 Hz. Two stimulation rates were also used: 500 and 4000 pps.

Procedure.

Loudness balancing.

The addition of AM to a signal increases the perception of loudness (McKay & Henshall, 2010), therefore loudness balancing of all experimental AM stimuli was performed. Loudness cues were limited using techniques suggested by Fraser and McKay (2012). Loudness balancing was performed using a loudness matching procedure for each AM depth, modulation frequency, and stimulation 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 to an AM target stimulus. Each target AM signal (for every modulation depth, at each modulation frequency, stimulation rate, and test electrode) was presented between two presentations of the unmodulated reference signal. 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 for a minimum of three trials. 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 modulation depth (1, 3, 5, 10, 25, 50, and 100%) at each stimulation rate (500 and 4000 pps) for each modulation frequency (50, 100, and 250 Hz) for two test electrodes. The procedure for selecting the test electrodes is specified below in the description of the ECAP amplitude growth functions.

AM detection.

AM detection thresholds (MDTs) were measured for two electrodes ([1] best ECAP slope, or “good” electrode; and [2] worst ECAP slope, or “poor” electrode). This was done at two stimulation rates (500 and 4000 pps). MDTs were measured using a three-interval, two-alternative forced-choice task with an inter-stimulus 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 percent 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 stimulation rate. Participants were instructed to select the "different" sound that may differ in sound quality, timbre, and/or pitch. No feedback was provided. The presentation of stimuli was blocked for different stimulation-rate conditions; the order of the electrodes tested in each rate block was randomized. The order of the conditions and electrodes tested was randomized across participants.

ECAP amplitude growth functions.

ECAP measurements were identical to the methods described for Study 1. For this study, two electrode locations were selected for the AM detection procedure out of five electrode locations measured (electrodes 4, 8, 12, 16, and 20). The electrode with the best (steepest AGF) response was selected as the participant's "good" electrode location, while the electrode with the worst (most shallow AGF) was selected as the participant's "poor" electrode location. In this way, AM detection was evaluated for each participant's best and worst electrode location as it relates to neural survival and/or the electrode-to-neural interface.

Statistical Analyses.

A three-level generalized linear (logistic) mixed-effects model (GLMM) was used to fit participants' AM detection performance. This was done in the R

Studio software interface, using the lme4 package (Bates, Maechler, Bolker, & Walker, 2014). The model building approach is similar to Study 1, which follows the recommendations of 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: stimulation 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% modulation (reference level), "1" = 5 and 10% modulation, "2" = 25, 50, and 100% modulation]. During experimental testing, the modulation depths included seven fixed levels. For analysis purposes, 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. Non-significant 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, DoD, 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 remain in the model represent changes to AM detection with increasing or decreasing that variable on a SD scale. Standardized ECAP slopes were designated as either the “good” or “poor” 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” = good (reference level), “1” = poor] 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 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 stimulation rate.

The results of the GLMM model are shown in Table 4. Results revealed significant main effects of modulation depth, modulation frequency, and stimulation rate on the detection of AM. As the modulation depth increased, the likelihood of detecting AM increased. At moderate depths of 5-10% modulation, participants were 2.17 times more likely to detect AM compared to small depths

1-3% ($p<0.001$). Participants were 3.97 times more likely to detect AM at large modulation depths of 25-100% compared to small depths ($p<0.001$). The modulation frequency also predicted AM detection performance, with slower modulation frequencies increasing the likelihood of AM detection. Compared to the highest modulation frequency of 250 Hz, participants were 1.75 times more likely to detect AM at 100 Hz ($p<0.001$). At 50 Hz, participants were 1.69 times more likely to detect AM compared to 250 Hz ($p<0.001$). This result reflects the low-pass characteristics of the auditory system for identifying the presence of modulated signals. Additionally, there was also a main effect of stimulation rate. Participants were 0.75 times less likely to detect AM with the faster stimulation rate of 4000 pps compared to 500 pps ($p=0.009$).

Table 4.
Final GLMM Model for AM Detection.

Fixed Effects	Coefficient	SE	Z	P	Odds	Odds Ratio
Intercept	**0.602**	**0.217**	**2.773**	**0.005**	1.83	1.00
Modulation Depth: Small [1 - 3 %] (ref)						
Moderate (5 - 10%)	**0.774**	**0.059**	**13.026**	**<0.001**	3.96	2.17
Large (25 - 100%)	**1.380**	**0.060**	**22.981**	**<0.001**	7.26	3.97
Modulation Freq: 250 Hz (ref)						
50 Hz	**0.526**	**0.055**	**9.632**	**<0.001**	3.09	1.69
100 Hz	**0.557**	**0.055**	**10.178**	**<0.001**	3.19	1.75
Stimulation Rate: 500 pps (ref)						
4000 pps	**-0.291**	**0.112**	**-2.589**	**0.009**	1.37	0.75
Age (standardized)	**-0.791**	**0.206**	**-3.845**	**<0.001**	0.83	0.45
Interactions						
Moderate Depth × 50 Hz	**0.787**	**0.094**	**8.400**	**<0.001**	14.72	8.06
Large Depth × 50 Hz	**1.685**	**0.156**	**10.833**	**<0.001**	66.19	36.24
Moderate Depth × 100 Hz	**0.736**	**0.094**	**7.867**	**<0.001**	14.43	7.90
Large Depth × 100 Hz	**1.168**	**0.131**	**8.926**	**<0.001**	40.75	22.31
Moderate Depth × 4000 pps	-0.085	0.081	-1.050	0.294	2.72	1.49
Large Depth × 4000 pps	**0.409**	**0.085**	**4.814**	**<0.001**	8.16	4.47
50 Hz × 4000 pps	**0.326**	**0.077**	**4.250**	**<0.001**	3.20	1.75
100 Hz × 4000 pps	**0.314**	**0.077**	**4.074**	**<0.001**	3.26	1.79
Moderate Depth × 50 Hz × 4000 pps	-0.105	0.127	-0.822	0.411	11.35	6.22
Large Depth × 50 Hz × 4000 pps	0.411	0.263	1.567	0.117	155.60	85.19
Moderate Depth × 100 Hz × 4000 pps	**-0.471**	**0.125**	**-3.772**	**<0.001**	8.47	4.64
Large Depth × 100 Hz × 4000 pps	-0.087	0.190	-0.459	0.646	57.52	31.49

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

Significant two-way interactions were identified between the depth of modulation and the modulation frequency. These four interactions, including Moderate depth × 50 Hz, Large depth × 50 Hz, Moderate depth × 100 Hz, and Large depth × 100 Hz, relate to AM performance in these conditions compared to 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 10 shows the mean AM detection performance functions for each experimental condition and highlights the interactions between modulation depth and modulation frequency.

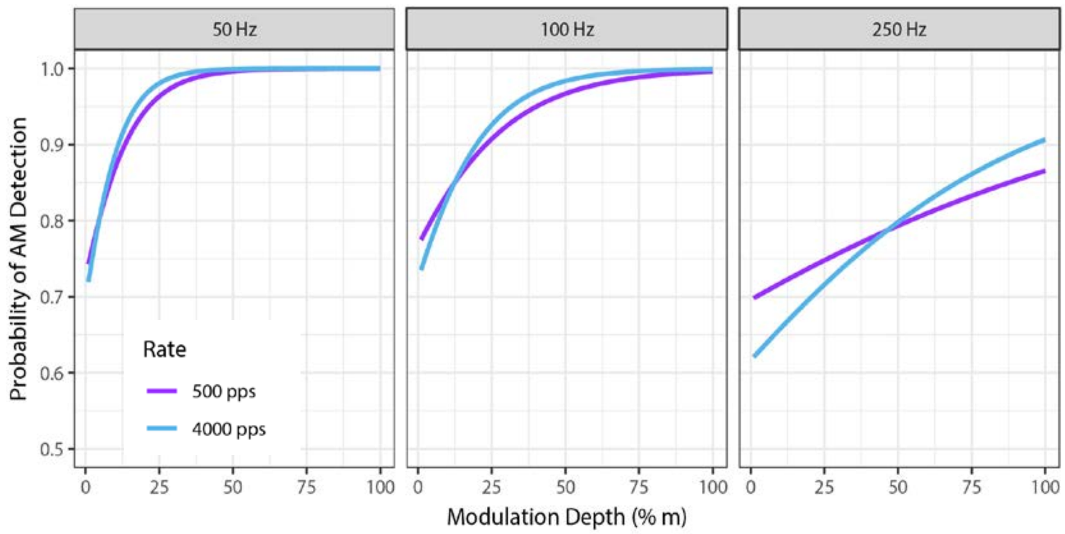


Figure 10. Mean performance functions for detecting AM at each modulation frequency and for each stimulation rate.

There was also 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 stimulation 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 stimulation rate to the same degree as compared to 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 stimulation rate was mitigated for larger modulation depths and for lower modulation frequencies, a participant was 4.64 times less likely to detect AM of moderate depths at 100 Hz at 4000 pps compared to the detection of small depths at 250 Hz at 500 pps (the reference). To summarize, this result suggests that the negative effect of increasing the stimulation 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 ($p<0.001$), suggesting that with every 1 SD increase in age (representing an interval of 18 years), a participant is 0.45 times less likely to detect AM overall. 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, DoD, or ECAP slope) were significant. This finding suggested that "good" electrodes did not exhibit significantly better MDTs compared to "poor" electrodes. Figure 11 displays the probability of AM detection when participants are broken up into three age groups: younger (age = SD<-1), middle-aged (age = -1<SD<1), and older (age = SD≥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.

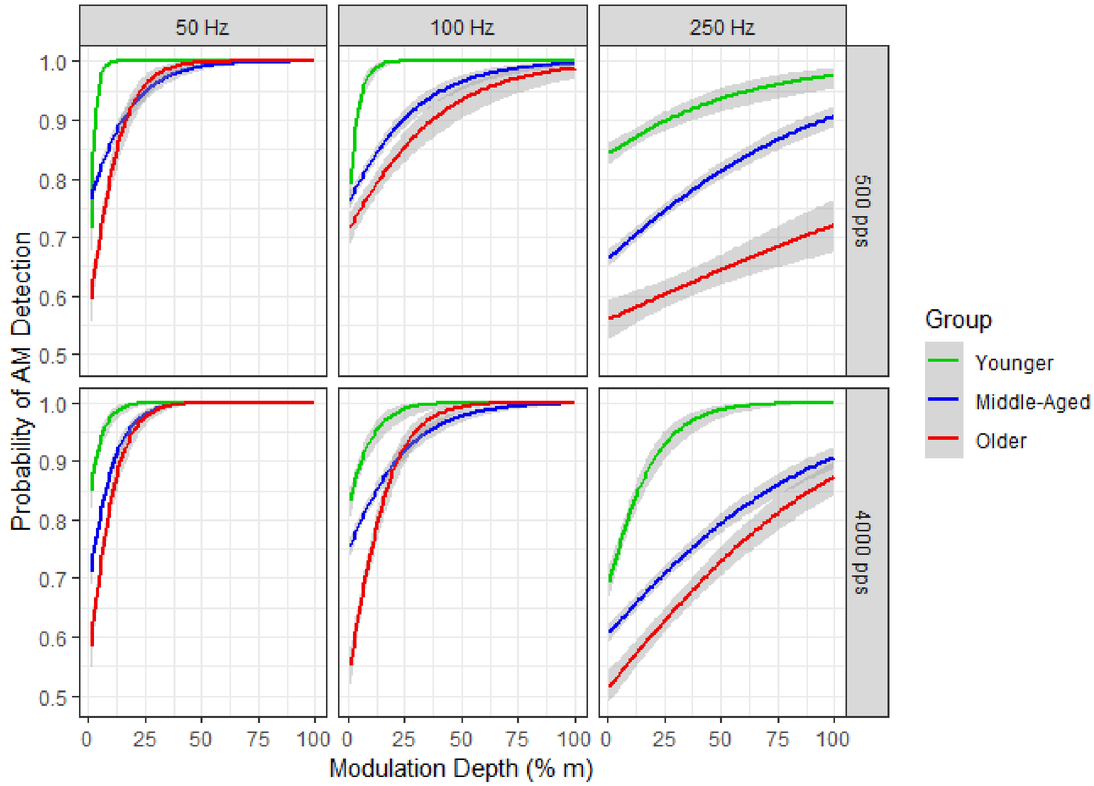


Figure 11. Mean performance functions for detecting AM in each experimental condition separated by age group. Green lines show performance for “Younger” participants ≤38 years of age (N=6; age values = SD≤-1]). Blue lines show “Middle-aged” participants between 39-73 years of age (N=10; age values = -1<SD<+1). Red lines show “Older” participants ≥74 years of age (N=6; age values = SD≥+1). Shaded areas around functions represent the standard error.

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 TMTFs are plotted as MDTs as a function of AM frequency for each stimulation rate in Figure 12. 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 12, which shows poorer MDTs with increasing age.

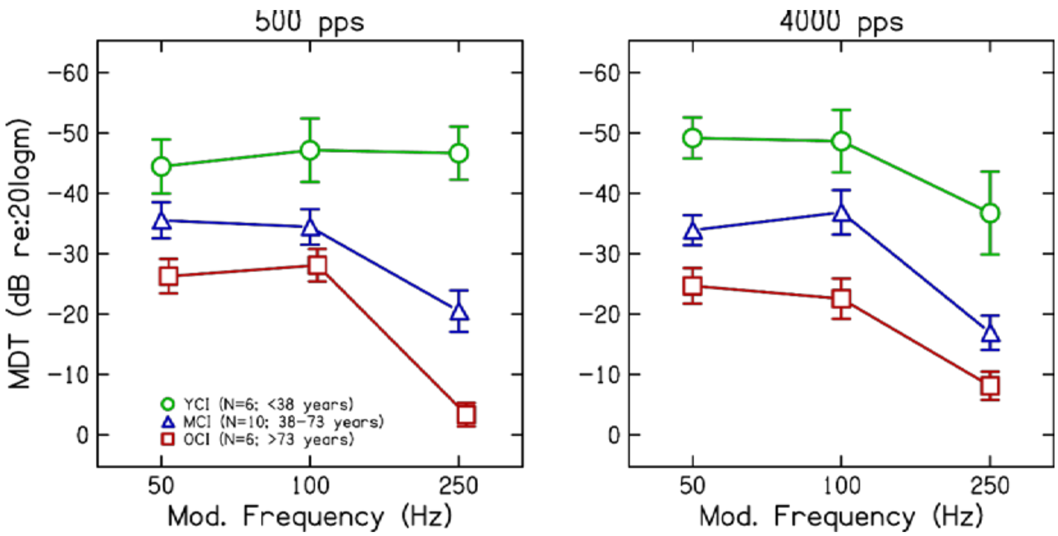


Figure 12. TMTFs (MDTs plotted as a function of modulation frequency) for each age group for the 500-pps stimulation rate condition (left panel) and the 4000-pps stimulation rate condition (right panel). Data points represent average group MDTs for both electrode locations for each modulation frequency condition. Error bars represent ±1 standard error.

ECAP slopes, including both sets of “good” and “poor” electrodes, are displayed in SD terms in Figure 13. These findings are similar to the ECAP values reported in Study 1 (Figure 6). On average, younger participants had steeper ECAP slopes compared to middle-aged and older participants, suggesting that peripheral neural survival declines with age.

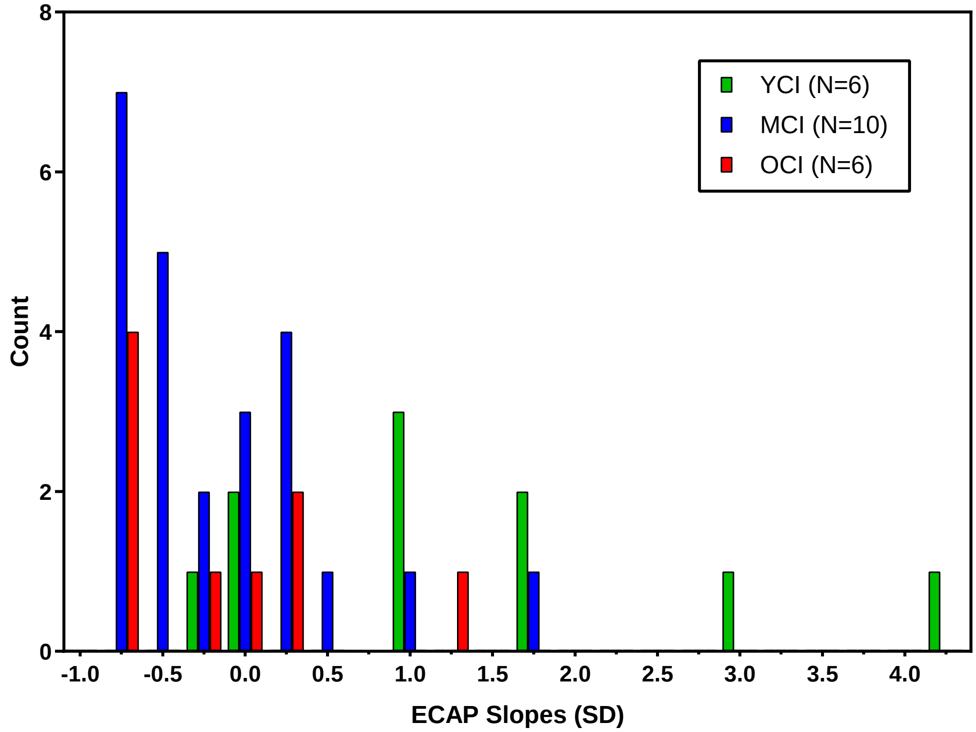


Figure 13. Frequency distributions of standardized ECAP slope values for the six YCI participants (green bars), 10 MCI participants (blue bars), and 6 OCI participants (red bars). An ECAP slope value of 0 represents the mean. Bin width represents 0.25 SDs.

Discussion

This study investigated the relative contributions of signal-related factors (including electrical stimulation rate, modulation frequency, and modulation depth), and listener-related factors (including chronological age, age at onset of hearing loss, DoD, and peripheral neural survival [as measured by ECAP slope]) to AM detection ability in adult CI users. Results showed a typical low-pass-filter pattern of detecting AM, which indicated poorer performance with increasing modulation frequency. Faster stimulation rates also resulted in slightly poorer AM detection overall. Chronological age was the only listener-related variable that predicted AM detection performance, with older participants requiring larger depths of modulation in order to accurately detect the presence of AM across all conditions. This finding suggested that a dynamic measure of central auditory temporal processing was strongly associated with participants' age and not with an estimate of peripheral neural survival.

Signal-related factors: Modulation depth, modulation frequency, and stimulation rate.

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 10 (p. 67) 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 between 8-36 times more likely to detect AM given any combination of depth (moderate and large) × frequency (50 and 100 Hz) when compared to the reference condition. The reference condition, which compared performance at a small depth, 250 Hz modulation frequency, and 500-pps stimulation rate to all other conditions, 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 stimulation rate compared to a 500-pps stimulation rate. Across all participants and all other stimulation rate parameters, AM was accurately detected 79% of the time at 500 pps and 77% of the time at 4000 pps. This suggested that participants were 0.75 times less likely to detect AM at a faster stimulation rate. Previous studies have also shown a decrease in AM detection performance with increasing the electrical stimulation rate (Galvin & Fu, 2005; Pfingst et al., 2007). Increases in the electrical stimulation 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 to a small DR. While some studies have found a significant correlation between DR and MDTs, suggesting that larger DRs are associated with better MDTs (e.g., Pfingst et al., 2007), other studies revealed that systematically increasing the DR for AM signals does not consistently result in improved AM detection performance (Galvin & Fu, 2005). The benefit from lower stimulation 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 stimulation rates. For higher stimulation rates, both the amplitude step size and the timing between successive pulses is much smaller as compared to lower stimulation rates.

There were significant interactions between modulation frequency and stimulation rate. This finding demonstrated that even though performance was poorer overall for 4000 pps compared to 500 pps, the stimulation rate effect was offset by increasing depths of modulation. Finally, a three-way interaction between Moderate depths × 100-Hz modulation frequency × 4000-pps stimulation rate suggested that the negative effect of a higher stimulation 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 would require larger depths of modulation compared to younger users to detect the present of AM in electrical pulse trains (Figure 11 and 12, pp. 69-70). 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. No other listener-related variables significantly predicted AM detection performance. Poorer performance as a result of advancing age was hypothesized to be a result of age-related auditory temporal processing limitations.

It was also hypothesized that the age differences would be largest for the faster stimulation 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 model showed only a significant main effect of age, and no significant cross-level interactions involving age. It is possible that the size of the rate effect was too small to significantly vary between age groups.

Additionally, there were no significant effects of any other listener-related variables (i.e., age at onset of hearing loss, DoD, or ECAP slope). This result is somewhat contradictory to previous studies that investigated the relationship between AM detection ability and estimates of peripheral neural survival (Garadat et al., 2012; Tejani, Abbas, & Brown, 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 maximal 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. (2017) and the current study is the methodology in collecting and interpreting the ECAP response. The current 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. Another difference between studies is the participants. The current study recruited 22 participants to represent a wide range of ages while the Tejani study recruited eight CI users, seven of whom were between the ages of 54-77 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.

A study by 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. The pattern of the across-site differences in MDTs were unique to each participant, with no systematic differences in MDTs as a function of tonotopic location across participants. These findings suggested that AM detection performance was related to participant-specific irregularities in the electrode-to-neural interface across the array. The current study found similar results, in that some participants had relatively large differences in MDTs across the two different electrode locations, while others did not. Ultimately, MDTs did not vary significantly as a function of electrode on the group level. 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 to their everyday programs, which had essentially all electrodes activated, participants had improved scores for speech-in-noise and consonant discrimination measures. This finding supported the hypothesis 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 is possible that ECAP AGFs are most sensitive to the number of surviving SGCs and not as sensitive to the more subtle neural degenerative changes that can occur with aging (e.g., altered temporal discharge patterns and/or demyelination). Thus, across-site variation in MDTs does exist and is potentially related to the quality of the electrode-to-neural interface. However, ECAP AGFs may not be the most sensitive measure in which to examine specific aspects of the electrode-to-neural interface that impact AM detection.

In the current study, which evaluated the respective contributions of central factors (i.e., chronological age) and peripheral factors (i.e., ECAP AGF slope) to a dynamic measure of auditory temporal processing ability, the only significant listener-related factor was age. This result is in contrast to the results for Study 1, which found that ECAPs were a stronger predictor of GDTs compared to age. However, some findings in the current study mirror what was found in Study 1.

Results supported the hypothesis that older participants would have more shallow ECAP slopes compared to younger participants, presumably because of age-related reductions in SGCs. One potential reason why ECAP slope did not significantly predict AM detection ability is because of the method of selecting one “good” and one “poor” electrode based on their respective ECAP slope values. This resulted in only two electrode locations per participant, as opposed to five electrode locations for Study 1. Another reason could be that the choice of a “good” vs “poor” 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, in some participants the slope value for the “good” electrode was substantially higher compared to all other electrodes. But in others, there were essentially little to no differences in slope values between the highest and lowest slope. For example, one participant only had a 2.7 µV difference in slope between electrodes, while another had a 42 µV difference. Regardless, ECAP slope was not a significant predictor of AM detection performance. Instead, chronological age was the sole listener-related factor that contributed to performance on this task. However, ECAP slope was correlated with age, with younger participants demonstrating steeper ECAP slopes compared to middle-aged and older participants (Figure 10, p. 67).

Another potential factor that could contribute to conflicting results between Study 1 and Study 2 is the nature of the task, which estimated auditory temporal processing ability. Gap detection is regarded as a “pure” measure of temporal processing because the signal is considered static. Alternatively, AM detection involves dynamic temporal coding (Walton, 2010). A dynamic form of temporal coding, as was used in the current study, could involve more higher-level encoding in the auditory system that could be differentially impacted by age.

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 tend to have earlier onset of hearing loss and are 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 is 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. Additionally, age was the only listener-related factor that significantly contributed to AM detection performance. However, Figure 13 (p.71) 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 slopes to investigate the contribution of peripheral factors separately.

Conclusions

This study investigated the effect of age and electrode choice on AM detection ability at a variety of electrical stimulation rates. It was hypothesized that results would show an age-related decline in central temporal processing ability for detecting AM. It was also expected that electrodes with a poor electrode-to-neural interface, presumably due to reduced peripheral neural survival (a reduction in SGCs) would have poorer AM detection ability compared to electrodes with a good electrode-to-neural interface. Results demonstrated that advancing age was associated with poorer AM detection performance overall. Peripheral status, as measured by ECAP AGF slopes, declined with age, but did not significantly contribute to AM detection ability.

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. However, the results of the current study reflect AM detection ability at the single-electrode level and do not necessarily reflect temporal envelope encoding for multi-electrode speech signals. In order to identify if the temporal processing deficits identified for single-electrode stimuli translate to more complex, multi-electrode stimulation, subsequent studies should be done using multi-electrode maps and more naturalistic speech signals (e.g., sentence stimuli presented in modulated and/or unmodulated noise).

Study 3: The Effect of Age on Word Recognition at Different Stimulation Rate and Modulation Frequencies

Introduction

While age impacted the results in Study 2, the question remained as to whether those age limitations would be observed for the recognition of speech signals. In order to examine whether age-related central auditory temporal processing deficits contributed to speech recognition limitations for older CI users, spoken words that varied in discrete temporal cues were presented to younger and older CI listeners using a variety of stimulation rates and envelope modulation frequencies. Results of this final study could provide insight into which stimulation parameters (e.g., optimal stimulation rate and envelope modulation frequency) could maximize performance for older CI users.

The effect of age on identification and discrimination of discrete temporal contrasts in unprocessed and CI-simulated speech.

Psychoacoustic studies have found age-related differences in the processing of simple, non-speech stimuli, including gap detection (Fitzgibbons & Gordon-Salant, 1994; He, Dubno, & Mills, 1998; Schneider et al., 1994; Snell, 1997) and duration discrimination (Fitzgibbons & Gordon-Salant, 1995) in normal-hearing listeners and listeners with hearing loss. In addition, other studies have evaluated how these temporal processing deficits may manifest in listeners' perception of speech signals. Gordon-Salant, Yeni-Komshian, Fitzgibbons, and Barrett (2006) measured the discrimination of temporal cues in speech segments in older adults with normal hearing, older adults with hearing loss, and younger adults with normal hearing. The stimuli presented to the younger group were presented with masking noise, which shifted audiometric thresholds to be equivalent to those of listeners in the older normal-hearing group. Listeners were presented with temporally based speech continua for word contrasts that varied in vowel duration (WHEAT/WEED), voice-onset time (VOT) (BUY/PIE), transition duration (BEAT/WHEAT), and silent interval duration (DISH/DITCH). Age-related differences were observed for discrimination of speech continua that differed in the feature of manner-of-articulation (BEAT/WHEAT and DISH/DITCH), suggesting that older listeners required longer temporal cues to discriminate between words that differed in these discrete temporal properties.

In a follow-up study, Goupell et al. (2017) presented the same DISH/DITCH continuum to younger and older normal-hearing listeners, but the stimuli were vocoded to simulate the spectral degradation that is characteristic of CI signal processing. Systematically reducing spectral and temporal information in the signal resulted in a reduced ability to distinguish between DISH and DITCH in both listener groups; however, reductions in spectral and temporal information in the signal caused larger declines in performance in the older listener group compared to the younger group. These results suggested that older listeners demonstrated reduced discrimination ability of discrete temporal cues for CI-simulated speech signals.

Other studies that presented CI-simulated, or vocoded, speech also revealed an effect of age for the identification of spectrally degraded speech signals (Schvartz et al., 2008; Souza & Boike, 2006; Souza & Kitch, 2001).

Schvartz et al. (2008) measured vocoded phoneme recognition in younger, middle-aged, and older normal-hearing listeners. The number of frequency channels and amount of frequency-to-place mismatch (to simulate a shallow insertion of the electrode array) was varied, resulting in conditions with differing levels of spectral distortion. When stimuli were severely degraded by limited channels and a greater frequency shift, younger listeners had better phoneme recognition than middle-aged and older listeners. Age of the listener and cognitive ability were the primary predictors of vowel recognition performance. Sheldon, Pichora-Fuller, and Schneider (2008) measured vocoded word-recognition abilities in younger and older adults as a function of the number of spectral channels needed to achieve 50% accuracy. When presented with randomized blocks of different channel conditions, older adults required approximately eight spectral channels, whereas younger adults needed only six spectral channels to reach 50% accuracy. Furthermore, studies have demonstrated that envelope modulation processing ability, which is another measure of temporal processing, is reduced in older listeners. Schvartz and Chatterjee (2012) measured fundamental frequency discrimination in younger and older listeners by varying the temporal envelope modulation frequency of vocoded stimuli. Results showed that in conditions with reduced spectral cues, younger listeners had better fundamental frequency discrimination when higher-frequency temporal envelope information was presented (>100 Hz), while older listeners did not show this improvement.

CI simulations vs. actual CI listeners.

Previous studies have also evaluated the effect of CI signal processing on the identification and discrimination of acoustic phonetic cues presented via electrical stimulation. Comparisons between studies that evaluated the recognition of temporal cues in CI-simulated speech presented acoustically and the recognition of those same cues presented via electrical stimulation of a CI electrode array should be interpreted with caution. This is because temporal representations within an electrically stimulated deaf ear are quite different than within an acoustically stimulated normal-hearing ear. In an electrically stimulated ear, there is an abnormally high degree of across-fiber synchrony in response to an electrical stimulus (Kiang & Moxon, 1972; Wilson, Finley, Lawson, & Zerbi, 1997) and the number of SGCs in the implanted ear will almost certainly be reduced compared to a normal-hearing ear (Hinojosa & Marion, 1983; Nadol Jr, Young, & Glynn, 1989). Additionally, surgical limitations resulting in a shallow insertion of the electrode array cause a frequency-to-place mismatch, or an upward spectral shift, in the frequency representations within the implanted cochlea. This spectral mismatch could cause distorted spectral representations and significant deficits in speech perception abilities (Dorman, Loizou, & Rainey, 1997; Fu & Shannon, 1999; Shannon, Zeng, & Wygonski, 1998).

Not only is it important to test these experimental paradigms in actual CI users, it is equally important to remove extraneous variables associated with testing CI listeners using a clinical sound processor. A clinical processor automatically manipulates incoming signals to present the most salient speech cues to its user. While these manipulations (e.g., AGC, real-time peak-picking strategies, and noise reduction algorithms) can improve speech recognition in real-world environments, they do not provide the ideal conditions under which to test the experimental questions at hand. AGC manipulations can reduce the modulation depth of incoming signals, depending on a participant's dynamic range. Peak-picking strategies will select different electrodes to stimulate in real time and are dependent on the participant's specific frequency-band allocation to each electrode. For this reason, the current study evaluated phoneme recognition ability for stimuli presented via direct stimulation of the electrode array using a research processor connected to a personal computer. This strategy allowed for examination of the effect of parametric signal variations on phoneme recognition ability in younger and older CI users, while avoiding unwanted signal distortions and unknown proprietary manipulations.

The effect of CI signal processing parameters on phoneme identification and word recognition.

In CI signal processing, temporal envelope and periodicity cues are represented by the electrical pulse train, which acts as the carrier signal for all temporal fluctuations. More rapid electrical pulse trains, or faster stimulation rates, deliver more electrical pulses per second to a given electrode. Faster rates should, in theory, sample the temporal envelope of the signal more accurately, and thus facilitate neural representations of the rapid modulations that carry short-duration speech segments (e.g., stop consonant bursts). From a digital signal processing standpoint, stimulation rate is essentially analogous to sampling rate, for which a higher rate should produce a higher fidelity signal representation. Consistent with this idea, studies have shown that higher rates of stimulation produce improvements in consonant identification. Loizou, Poroy, and Dorman (2000) measured consonant and monosyllabic word recognition by CI listeners using electrical stimulation rates from 400-2100 pps. Higher stimulation rates produced a significant benefit to consonant recognition, primarily because higher rates allowed for more accurate identification of the manner-of-articulation for a given consonant. This effect is highlighted in Figure 14, which is taken from Loizou et al. (2000), and shows the pulsatile waveforms of the syllable /ti/ obtained at different rates of stimulation. As the stimulation rate increases, the burst portion of the speech segment becomes more distinctive.

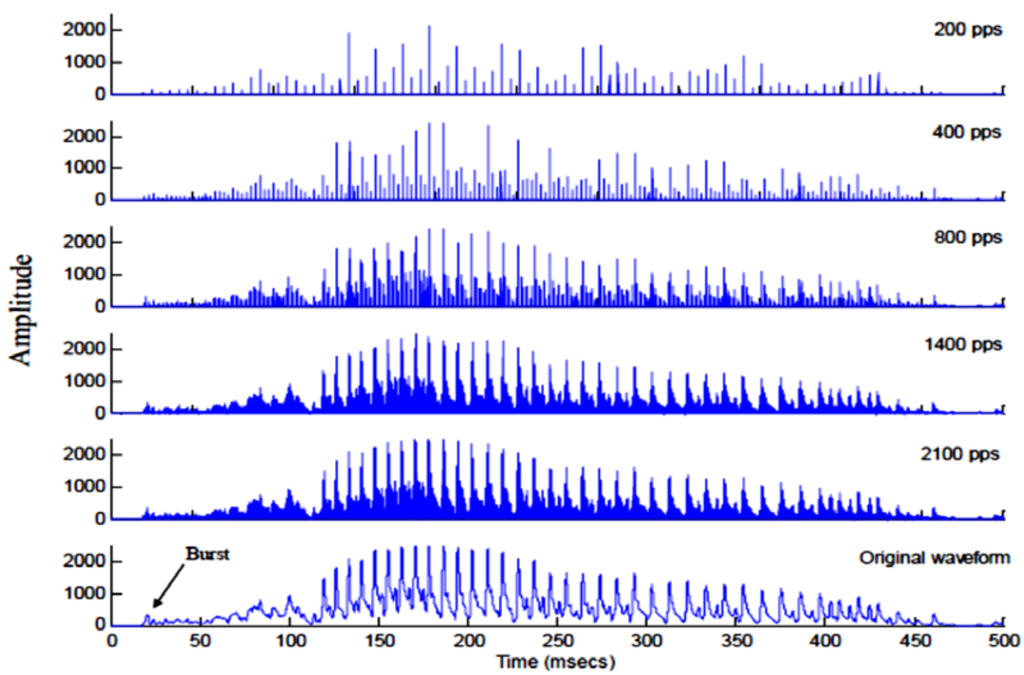


Figure 14. Figure taken from Loizou et al. (2000) to show the effect of stimulation rate on the representation of a short-duration speech segment (e.g., burst).

Loizou et al. (2000) also showed that monosyllabic word recognition improved with increasing stimulation rate on the group level, but there was significant individual variability. Some participants improved more than others with a higher rate, while others performed best with a moderate rate. The small number of participants in Loizou et al. (2000) (N=6) precluded the assessment of individual subject variables that may have contributed to the mixed effects of stimulation rate on word recognition. In another study, the interaction between stimulation rate and age on speech recognition ability in CI users was examined by Shader *et al.* (under review). Results from 37 CI users, ranging in age from 22-87 yrs, revealed that speech recognition scores declined as a function of age. On a group level, scores also increased with increasing stimulation rate, which was similar to the findings observed by Loizou et al. (2000). However, the subset of older CI users demonstrated improved speech recognition ability when using the lowest stimulation rate. These results suggest that chronological age may contribute to the individual variability among CI users observed in studies that evaluated speech recognition as a function of stimulation rate, but did not consider age as a variable.

Summary and hypotheses.

Studies 1 and 2 of this research were concerned with identifying age-related differences in the detection of temporal alterations in non-speech signals delivered to single electrodes in CI users. This final study expands on the findings from the first two studies by examining the effect of age on the identification of consonants embedded within words that differ in discrete temporal cues delivered via a typical CI speech processing strategy. While the first two studies were designed to establish age-related central auditory temporal processing deficits for non-speech stimuli, this final study bridged the gap between the psychophysical measurements in Studies 1 and 2 and participants' perception of speech signals that differ in the temporal domain.

Stimuli for this final study were chosen to represent a range of temporal contrasts that cue phoneme identity. The perception of these chosen contrasts was also expected to be altered by parametric variations in electrical stimulation, including the rate of stimulation and the envelope modulation frequency. The contrasts included word pairs that differed in consonant voicing (i.e., VOT, onset of voicing following frication, and vowel duration) and manner-of-articulation. VOT is the duration of the interval between the release burst and the onset of vocal fold vibration, and is the primary cue to distinguish voicing for a consonant plosive in the word-initial position (Lisker & Abramson, 1964). For fricatives in the word-initial position, the primary cue to voicing is the relative onset of voicing following frication. Another cue to voicing is vowel duration, which is the primary cue to post-vocalic consonant voicing for stops and fricatives (Denes, 1955; Luce & Charles-Luce, 1985; Peterson & Lehiste, 1960). The duration of the vowel preceding the final consonant is longer for voiced consonants than for voiceless consonants. The duration of the silent interval between the release burst and onset of frication is the primary cue used to distinguish between a fricative and an affricate, which differ in manner of articulation (Dorman, Raphael, & Liberman, 1979).

The goal of Study 3 was to identify the effect of age among CI users on the perception of phonemes that vary in discrete temporal cues. It was hypothesized that younger participants would achieve better target phoneme recognition scores compared to older participants, potentially because of age-related temporal processing deficits. It was also hypothesized that the presence of higher-frequency envelope modulations would improve phoneme recognition for all participants, but that younger participants would be able to take advantage of the higher-frequency modulations to a greater extent compared to the older participants. Stimulation rate was expected to impact the results for older participants in particular, with older participants benefitting from lower stimulation rates compared to higher rates. It is of interest to investigate whether phoneme recognition errors could be reduced with modifications to the electrical stimulation parameters for older CI users. Such a finding would be clinically relevant and would suggest the need for developing patient-specific and age-specific CI mapping strategies. Given that cognitive capacity declines with advancing age, it was hypothesized that scores on various cognitive measures would significantly contribute to phoneme recognition ability.

Method

Participants.

Twenty participants were recruited to represent a range of ages between 27 and 85 years (mean=59.8 ± 18.2 years). All participants were required to pass a cognitive screening for dementia with a score of ≥22 on the Montreal Cognitive Assessment (MoCA) (Nasreddine et al., 2005). Cognitive performance was used to account for potential variance in addition to age, therefore it was important to exclude cognitive impairment as a factor underlying performance. All participants were implanted with Cochlear-brand devices and were required to have at least one year of CI experience. All participants were native speakers of American English. Participant demographics are shown in Table 5.

Table 5.
Participant Demographics Table: Study 3.

Participant	**Age**	**Gender**	**Age at HL Onset**	**DoD**	**Etiology**	**Device**
CAR	27	M	4	15	Hereditary	CI24RE(CA)
CDA	28	F	0	20	Connexin 26	CI512(CA)
CAT	32	M	10	9	Hereditary	CI24RE(CA)
CBP	39	F	5	15	Hereditary	CI24M
CCS	42	M	1	37	Meningitis	CI422
CBW	46	M	26	5	COGAN Syndome	CI24R(CS)
CAP	51	F	38	1	Hereditary	CI24RE(CA)
CAS	55	F	41	3	Hereditary	CI24RE(CA)
CDB	60	F	27	22	Hereditary	CI24RE(CA)
CBF	61	M	5	47	Hereditary	CI24RE(CA)
CBR	66	F	0	57	Unknown	CI24RE(CA)
CCR	70	F	2	60	Unknown	CI512(CA)
CAK	73	M	34	36	Ototoxicity	CI422
CAF	73	F	5	49	Unknown	CI24RE(CA)
CAO	74	F	3	63	Rheumatic fever	CI512(CA)
CAM	75	F	40	24	Unknown	CI24RE(CA)
CCA	79	M	70	1	Ototoxicity	CI512(CA)
CAD	79	M	55	10	Unknown	CI24RE(CA)
CBC	81	F	70	1	Sudden SNHL	CI24RE(CA)
CBB	85	M	77	2	Aging	CI24RE(CA)

Note. HL=hearing loss; DoD=duration of deafness; SNHL=sensorineural hearing loss.

Stimuli.

The stimuli consisted of 96 monosyllabic consonant-vowel-consonant (CVC) words and were a subset of the word tokens used in Gordon-Salant, Yeni-Komshian, and Fitzgibbons (2010). The words were selected to represent pairs of contrasting consonants that differ within the temporal domain. The consonant contrasts differed in (1) VOT to cue voicing for stops (/b-p/, /d-t/, and /g-k/), (2) the relative onset of frication and voicing to cue voicing for fricatives (/v-f/ and /z-s/), (3) silence duration between the release burst and frication for a fricative/affricate contrast (ʃ-tʃ), and (4) vowel duration to cue post-vocalic voicing (/s-z/, /f-v/, /k-g/, /t-d/, /p-b/). Each contrast pair was tested using four word pairs in both the word-initial and word-final position, resulting in a total of eight word pairs (16 words) representing each consonant contrast. Thus, for each set of 96 CVC words, 24 words differed in VOT (VOT category), 16 words differed in the onset of voicing following frication (Onset Frication category), 16 words differed in the silence duration between the release burst and frication (Silence Duration category), and 40 words differed in vowel duration (Vowel Duration category). Each word pair was matched as closely as possible on frequency of occurrence within the American English language according to the Kučera and Francis (1967) word counts. Each CVC word and its respective phoneme contrast are specified in Table 6.

Table 6.
CVC Word Stimuli for Each Consonant Contrast.

Consonants	**Pair 1**		**Pair 2**		**Pair 3**		**Pair 4**	
/p/ /b/ initial	Bun	Pun	Bin	Pin	Bear	Pear	Beach	Peach
/t/ /d/ initial	Din	Tin	Deer	Tear	Duck	Tuck	Dip	Tip
/k/ /g/ initial	Goal	Coal	Gain	Cane	Gap	Cap	Ghost	Coast
/f/ /v/ initial	Vase	Face	Van	Fan	Veal	Feel	Veil	Fail
/s/ /z/ initial	Sink	Zinc	Sip	Zip	Sue	Zoo	Seal	Zeal
/tʃ/ /ʃ/ initial	Cheap	Sheep	Chair	Share	Cheer	Sheer	Chew	Shoe
/p/ /b/ final	Rib	Rip	Cob	Cop	Mob	Mop	Lobe	Lope
/t/ /d/ final	Seed	Seat	Code	Coat	Weed	Wheat	Toad	Tote
/k/ /g/ final	Tug	Tuck	Rag	Rack	Tag	Tack	Bug	Buck
/f/ /v/ final	Leave	Leaf	Live	Life	Save	Safe	Five	Fife
/s/ /z/ final	Dies	Dice	Raise	Race	Lose	Loose	Buzz	Bus
/tʃ/ /ʃ/ final	Ditch	Dish	Hatch	Hash	Catch	Cash	Latch	Lash

The stimuli were recorded by a young, normal-hearing male who was a native speaker of American English. The recordings used in the current study were the original recordings as used in Gordon-Salant et al. (2010). The speaker was instructed to read each word aloud in a typical conversational manner. The stimuli were edited to select word tokens that were free of extraneous sounds and distortion. The level of the words was adjusted to create word tokens that were equivalent in root-mean-square (rms) energy. Word tokens were presented following a carrier phrase ("I'd like you to say…") spoken by the same speaker that recorded the CVC word stimuli.

Stimuli were presented to listeners through direct stimulation of the electrode array. The acoustic stimuli were digitally processed and delivered to the array using the Continuous Interleaved Sampling (CIS) speech processing strategy. Figure 15 shows a block diagram taken from Loizou (2006) to illustrate the digital signal processing involved with the CIS processing strategy. First, a pre-emphasis filter is used to attenuate low-frequency components within the signal that may otherwise mask the weaker, but important high-frequency components. The signal is filtered into individual frequency channels using a series of bandpass filters (BPFs). The output of each BPF is then full-wave rectified and low-pass filtered (LPF) (likely with a 200 Hz cut-off frequency) to extract the temporal envelope of that frequency band. The extracted envelopes are then compressed to fit the limited DR of electrical hearing and are used to modulate electrical pulse trains delivered to individual electrodes in a non-overlapping (non-simultaneous) fashion. In this way, only one electrode is stimulated at a time, which reduces the interaction between individual electrodes due to the summation of their electrical fields.

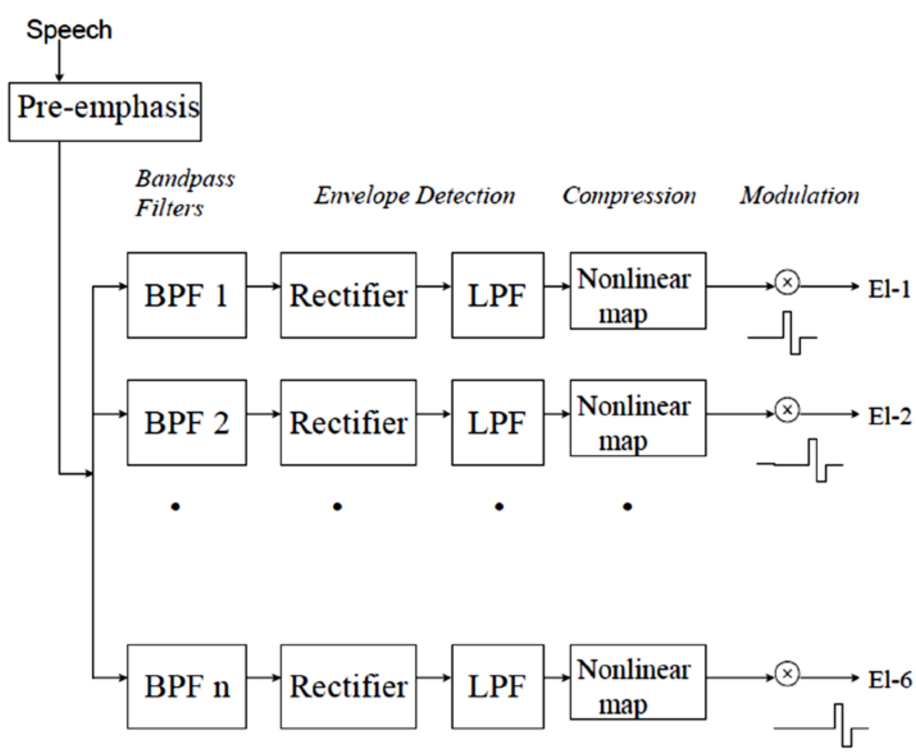


Figure 15. Schematic taken from Loizou (2006). Block diagram of CIS signal processing. BPF=bandpass filter. LPF=low-pass filter.

For the current experiment, an eight-channel CIS strategy was used to allow for sufficient separation between stimulating electrodes in order to reduce the possible effects of electrode interaction (Middlebrooks, 2004). To examine the effect of stimulation rate on phoneme recognition, experimental maps with stimulation rates of 500, 900, and 1800 pps were created. The 500-pps rate was chosen to represent a lower rate of stimulation that has been shown to improve speech recognition scores in older CI users compared to higher rates (Shader *et al.,* under review). The 900-pps rate was chosen to represent the default stimulation rate that is recommended by Cochlear Ltd. for all CI users. The 1800-pps rate was chosen as the fastest stimulation rate, which represents a doubling of the default rate. To examine the effect of envelope modulation frequency, acoustic stimuli were low-pass filtered, resulting in a “smeared” temporal envelope which reduced the maximum envelope modulation rate to 50 Hz. Envelope smearing was performed to evaluate the potential mechanism (i.e., temporal processing deficits) underlying the age-related performance gap between younger and older CI users. Envelope smearing was applied in the same manner as described by Drullman, Festen, and Plomp (1994). Briefly, the rate of envelope fluctuations in the signal was limited by low-pass filtering the bandpass filtered envelopes using a 50 Hz cut-off frequency. An “unfiltered” condition was also tested, which utilized the standard CIS envelope extraction method, resulting in at least a 200 Hz-LPF cut-off frequency (this cut-off frequency is an approximation as the maximum modulation frequency conveyed via CIS processing is ultimately determined by the bandwidth of a given frequency channel; see Table 7). Example waveforms of the word “peach” for the unfiltered and 50 Hz envelope conditions are shown in Figure 16. All 96 CVC words were tested in each stimulation rate (three rates) × envelope filtering (two modulation frequencies) condition. This resulted in six stimulation rate × envelope filtering conditions. The order of the 96 test stimuli was randomized for each presentation, with the exception that the two words that represented a specific consonant contrast (a word pair) were not presented consecutively. The order of stimulation rate × modulation frequency conditions was also randomized for each participant.

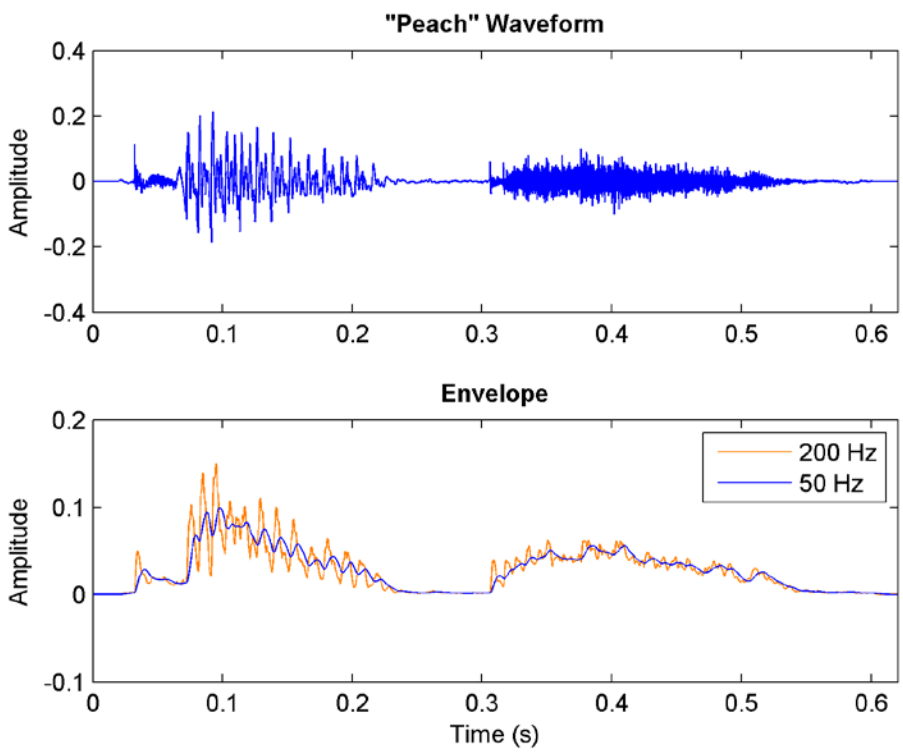


Figure 16. Original waveform of the word “peach” is plotted on the top panel. The summed temporal envelopes for the eight-channel processed stimuli after envelope filtering are shown in the bottom panel. Orange line = the “unfiltered” stimuli that is inherently filtered at ~200 Hz during standard CIS processing. Blue line = the 50-Hz LPF stimuli used in the envelope filtering condition.

Procedure.

Mapping.

Typical clinical mapping procedures were used to create three experimental maps, each using a different stimulation rate (500, 900, and 1800 pps). Threshold (T) and comfort (C) levels were measured on each of the eight electrodes corresponding to the eight channels that were active during CIS stimulation (electrodes # 4, 7, 10, 14, 16, 18, 20, 22). If any of these electrodes were deactivated in a participant's clinical map, the closest adjacent electrode was chosen as its replacement. Further adjustments for loudness/comfort and sound-quality issues after initial measurement were limited to global increases or decreases in T and/or C levels, and directional tilting either clockwise (increase low-frequency, decrease high-frequency channels) or counterclockwise (increase high-frequency, decrease low-frequency channels). Table 7 shows the frequency allocation table of an eight-channel CIS map and the corresponding bandwidths of each channel.

Table 7.
Frequency Allocation of Experimental Eight-Channel CIS Maps.

	CIS Channel Number							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Electrode	**E22 (apical)**	**E20**	**E18**	**E16**	**E14**	**E10**	**E7**	**E4 (basal)**
Lower Freq (Hz)	188	438	688	1063	1563	2313	3438	5188
Upper Freq (Hz)	438	688	1063	1563	2313	3438	5188	7938
Bandwidth (Hz)	250	250	375	500	750	1125	1750	2750

Phoneme recognition testing.

The stimuli were presented via direct stimulation of the electrode array using an Auxcon software interface and a L34 research sound processor. Stimuli were presented at the equivalent current level to a clinical speech processor as if the speech was presented at an RMS level of 57 dB SPL with the default microphone sensitivity setting. Typically, this results in stimulation levels between 70-85% of the electrical DR depending on the signal spectrum. This strategy replicated the current levels that would be used in clinical CI processors for speech arriving at the microphone at a conversational volume.

Prior to testing, a brief practice/acclimatization session was provided to familiarize each participant to each experimental map. Participants were instructed to listen to the stimulus and to repeat back the last word following the carrier phrase (i.e., open-set response). Guessing was encouraged. Responses were scored for overall percent correct for target phoneme identification in each stimulation rate × modulation frequency condition. In addition, the responses were evaluated for error types for each consonant contrast.

Cognitive measures.

In addition to the MoCA screening tool for dementia, all participants completed cognitive measurements to estimate their speed of processing, working memory, and attention abilities using the NIH Toolbox (Gershon *et al.*, 2013), administered on a tablet. Assessments in these cognitive domains were included to determine the contribution of cognitive ability to phoneme recognition performance (CHABA, 1988). Speed of processing was measured with the

Pattern Comparison Processing Speed test, as well as by the response time measure of the Flanker test. Working memory was measured with the List Sorting and Picture Sequence Working Memory tests. Attention was measured by the accuracy score of the Flanker test and the Dimensional Change Card Sort test. These cognitive abilities are known to decline with age (Park et al., 2002; Salthouse, 1991; West & Alain, 2000) and it was important to consider the contribution of cognitive differences between ages in interpreting the results. The uncorrected standard scores for these cognitive assessments were then used as potential predictor variables in planned analyses.

Statistical Analyses.

A similar analysis procedure as described in Study 2 was used to evaluate the effects of signal-related factors as well as subject-related factors to phoneme recognition performance. Four, two-level generalized linear (logistic) mixed-effects models (GLMMs) were used to fit participants' phoneme recognition scores in reference to each consonant contrast. In other words, the same data set was analyzed four separate times; each time the data were releveled so that a different group of consonant contrasts was used as the reference condition. This approach was chosen in order to observe the effects of predictor variables for each group of consonants specifically, as well as to evaluate pairwise comparisons between the groups themselves. It is important to note that separating the word tokens into different consonant groups for data analysis did not provide information regarding the *type* of error that was made. For example, errors for words that fell into the VOT category could have comprised any type of error due to the open-set nature of the task, including a VOT error in voicing (e.g., “bun” for “pun”) or a non-VOT error in either place-of-articulation (e.g., “tun” for “pun”) or manner-of-articulation (e.g., “sun” for “pun”). For this analysis, the dependent variable was either a “1” or a “0,” in which a correct response was assigned a “1” while any incorrect response was labeled as a “0.” Error pattern analysis was done separately and is described in the Results section below. The level-1 predictor variables were as follows: contrast category [four levels: “1” = VOT, “2” = Onset Frication, “3” = Silence Duration, “4” = Vowel Duration], stimulation rate [three levels: “-1” = 500 pps, “0” = 900 pps (reference level), “1” = 1800 pps], and filter condition [two levels: “0” = unfiltered (reference level), “1” = 50 Hz low-pass filter]. The level-2 predictor variables included chronological age, age at onset of deafness, DoD, and cognitive measures (List Sorting, Pattern Comparison, Picture Sequence, Flanker [accuracy measure], and Dimensional Card Sort). All values for the level-2 predictors were standardized (z-scores) before being entered into the models. The same model-building procedure and strategy for variable selection as described in Study 2 were used to analyze each of the four phoneme-recognition models.

Results

Effects of contrast category, stimulation rate, and envelope filtering.

The results of the four GLMM models are shown in Table 8. Results revealed significant effects of contrast category, envelope filtering using a 50-Hz LPF cut-off frequency, and DoD. In general, phoneme recognition scores for consonants falling in the VOT category were significantly higher than the other three categories. For phonemes representing the Onset of Frication, Silence Duration, and Vowel Duration categories, participants were between 0.61-0.72 times less likely to recognize the target phoneme compared to the VOT category (p<0.001). In addition, performance in the Onset Frication category was significantly poorer when compared to the Vowel Duration category. Participants were 1.19 times more likely to recognize the target phoneme in the Vowel Duration category compared to the Onset Frication category (p=0.029).

Table 8.
GLMM Results for the VOT Reference Category.

Fixed Effects	Coefficient	SE	Z	P	Odds	Odds Ratio
(1) VOT						
Intercept	0.22	0.15	1.42	0.156	1.24	1
50 Hz Filtering	**-0.65**	**0.09**	**-7.27**	**<0.001**	0.65	0.52
Category: (1) VOT (ref)						
(2) Onset of Frication	**-0.50**	**0.09**	**-5.64**	**<0.001**	0.75	0.61
(3) Silence Duration	**-0.39**	**0.09**	**-4.35**	**<0.001**	0.84	0.68
(4) Vowel Duration	**-0.32**	**0.07**	**-4.59**	**<0.001**	0.90	0.72
Duration of Deafness (standardized)	**-0.30**	**0.15**	**-2.06**	**0.039**	0.92	0.74
Interactions						
50 Hz × (2) Onset of Frication	**0.51**	**0.13**	**4.10**	**<0.001**	0.66	0.53
50 Hz × (3) Silence Duration	0.24	0.13	1.93	0.053	0.56	0.45
50 Hz × (4) Vowel Duration	-0.06	0.10	-0.62	0.533	0.44	0.35
50 Hz × Duration of Deafness	**0.21**	**0.06**	**3.74**	**<0.001**	0.60	0.48
(2) Onset of Frication						
Intercept	-0.29	0.16	-1.80	0.072	0.75	1.00
50 Hz Filtering	-0.14	0.11	-1.29	0.196	0.66	0.87
Category: (2) Onset of Frication (ref)						
(1) VOT	**0.50**	**0.09**	**5.64**	**<0.001**	1.24	1.65
(3) Silence Duration	0.12	0.10	1.20	0.230	0.84	1.12
(4) Vowel Duration	**0.18**	**0.08**	**2.18**	**0.029**	0.90	1.19
Duration of Deafness (standardized)	**-0.30**	**0.15**	**-2.06**	**0.039**	0.56	0.74
Interactions						
50 Hz × (1) VOT	**-0.51**	**0.13**	**-4.09**	**<0.001**	0.65	0.86
50 Hz × (3) Silence Duration	**-0.27**	**0.14**	**-1.97**	**0.049**	0.56	0.75
50 Hz × (4) Vowel Duration	**-0.58**	**0.12**	**-4.98**	**<0.001**	0.44	0.59
50 Hz × Duration of Deafness	**0.21**	**0.06**	**3.74**	**<0.001**	0.60	0.80
(3) Silence Duration						
Intercept	-0.17	0.16	-1.07	0.285	0.84	1.00
50 Hz Filtering	**-0.41**	**0.11**	**-3.84**	**<0.001**	0.56	0.67
Category: (3) Silence Duration (ref)						
(1) VOT	**0.39**	**0.09**	**4.35**	**<0.001**	1.24	1.47
(2) Onset of Frication	-0.12	0.10	-1.20	0.229	0.75	0.89
(4) Vowel Duration	0.06	0.08	0.75	0.454	0.90	1.06
Duration of Deafness (standardized)	**-0.30**	**0.14**	**-2.06**	**0.039**	0.63	0.74
Interactions						
50 Hz × (1) VOT	-0.24	0.13	-1.93	0.053	0.65	0.77
50 Hz × (2) Onset of Frication	**0.27**	**0.14**	**1.97**	**0.048**	0.66	0.78
50 Hz × (4) Vowel Duration	**-0.31**	**0.12**	**-2.64**	**0.008**	0.44	0.52
50 Hz × Duration of Deafness	**0.21**	**0.06**	**3.74**	**<0.001**	0.52	0.61
(4) Vowel Duration						
Intercept	-0.11	0.15	-0.73	0.467	0.90	1.00
50 Hz Filtering	**-0.71**	**0.08**	**-9.49**	**<0.001**	0.44	0.49
Category: (4) Vowel Duration (ref)						
(1) VOT	**0.32**	**0.07**	**4.59**	**<0.001**	1.24	1.38
(2) Onset of Frication	**-0.18**	**0.08**	**-2.18**	**0.029**	0.75	0.84
(3) Silence Duration	-0.06	0.08	-0.75	0.454	0.84	0.94
Duration of Deafness (standardized)	**-0.30**	**0.14**	**-2.06**	**0.039**	0.67	0.74
Interactions						
50 Hz × (1) VOT	0.06	0.10	0.62	0.533	0.65	0.72
50 Hz × (2) Onset of Frication	**0.58**	**0.12**	**4.99**	**<0.001**	0.66	0.73
50 Hz × (3) Silence Duration	**0.31**	**0.12**	**2.64**	**0.008**	0.56	0.63
50 Hz × Duration of Deafness	**0.21**	**0.06**	**3.74**	**<0.001**	0.40	0.45
Random Effects	**Variance**	**SD**				
Subject Intercept	0.41	0.64				
Subject: Filter Slope	0.03	0.18				

Phoneme recognition did not vary significantly as a function of stimulation rate. Furthermore, stimulation rate did not significantly improve model fit for any of the four models. The effect of envelope smearing, however, did significantly impact phoneme recognition performance. Low-pass filtering the signal at 50 Hz resulted in poorer performance in each contrast category except for Onset Frication. For the other three categories, participants were between 0.49-0.67 times less likely to correctly recognize the target phoneme with envelope filtering compared to the unfiltered stimuli (p<0.001).

There were also significant two-way interactions between envelope filtering and contrast category in each model. Figure 17 highlights these interactions and shows the mean phoneme recognition performance for each contrast category and filtering condition. Comparison between the fixed effects coefficients across the four models revealed that the negative impact of envelope filtering was largest in the Vowel Duration category, then the VOT category, then Silence Duration, and finally Onset Frication. To investigate the nature of the two-way interactions, each model was releveled by assigning the envelope filtering reference condition to 50-Hz filtering. The magnitude of the filtering effect was not significantly different between the Vowel Duration and VOT categories. However, comparisons between the Vowel Duration category and the Onset Frication and the Silence Duration categories revealed that filtering did not impact the latter categories to the same extent as in the Vowel Duration category. For the VOT reference category, the effect of filtering was similar to the other categories except for Onset Frication. In relation to the Silence Duration reference category, the effect of filtering was significantly less for Onset Frication and significantly greater for Vowel Duration. There was not a significant difference in filtering between the Silence Duration and VOT categories. Finally, compared to Onset Frication, the effect of filtering was greater in every other contrast category. To summarize, because there was no main effect of envelope filtering in the Onset Frication model, there were multiple two-way interactions between contrast category and envelope filtering.

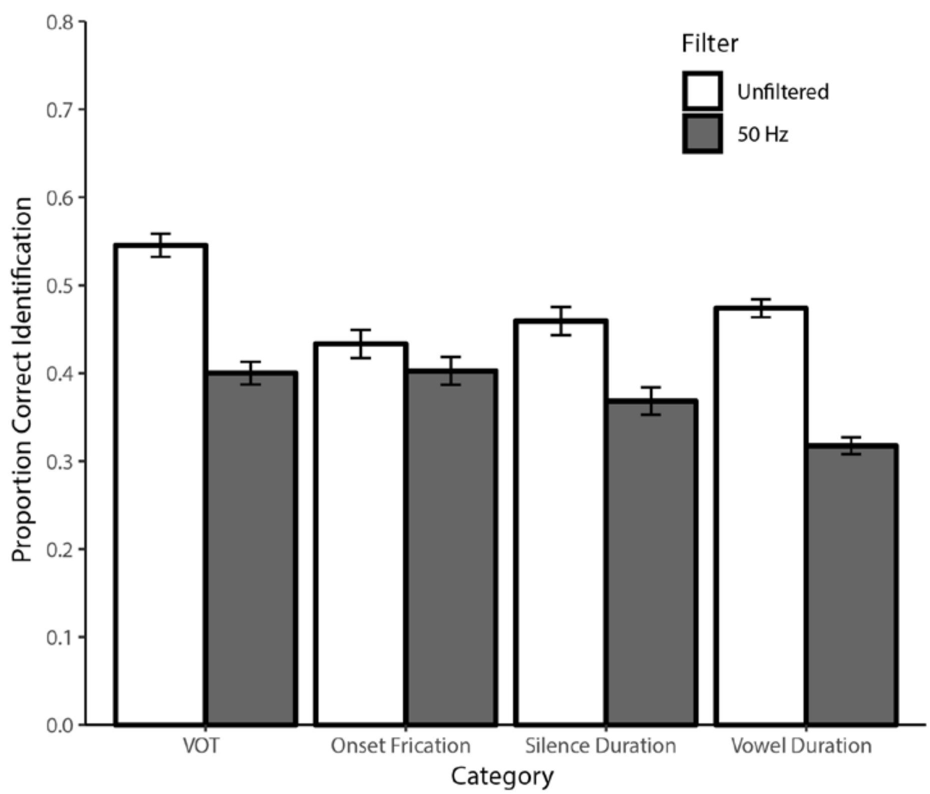


Figure 17. Mean proportion of correct phoneme identification in each consonant contrast category for both envelope filtering conditions. White bars represent mean data for Unfiltered stimuli. Grey bars represent mean data for stimuli filtered at 50 Hz. Error bars = ± 1 standard error.

Effects of age, age at onset, duration of deafness, and cognition.

The only subject-level variable that significantly predicted target phoneme recognition performance was DoD. The main effect of DoD was the same across all category models. DoDs in this data set ranged from 1-64 years (mean=25.1±21.8 years). Results suggested that with every 1 SD increase in DoD, participants were 0.74 times less likely to correctly recognize the target phoneme for each contrast category ($p=0.039$).

Results also showed significant two-way interactions between DoD and envelope filtering. This finding suggested that prolonged DoDs were associated with poorer phoneme recognition performance, but that this relationship was stronger in the unfiltered condition compared to the 50-Hz filtering condition. Figure 18 shows individual participant mean data points for each consonant contrast category for the unfiltered and the filtered stimuli. Regression lines are also plotted to show the predicted model fit for each category and filtering condition. The predicted data lines demonstrate the difference in the relationship between DoD and performance between the filtering conditions, with steeper slopes in the unfiltered condition compared to the 50-Hz filtering condition.

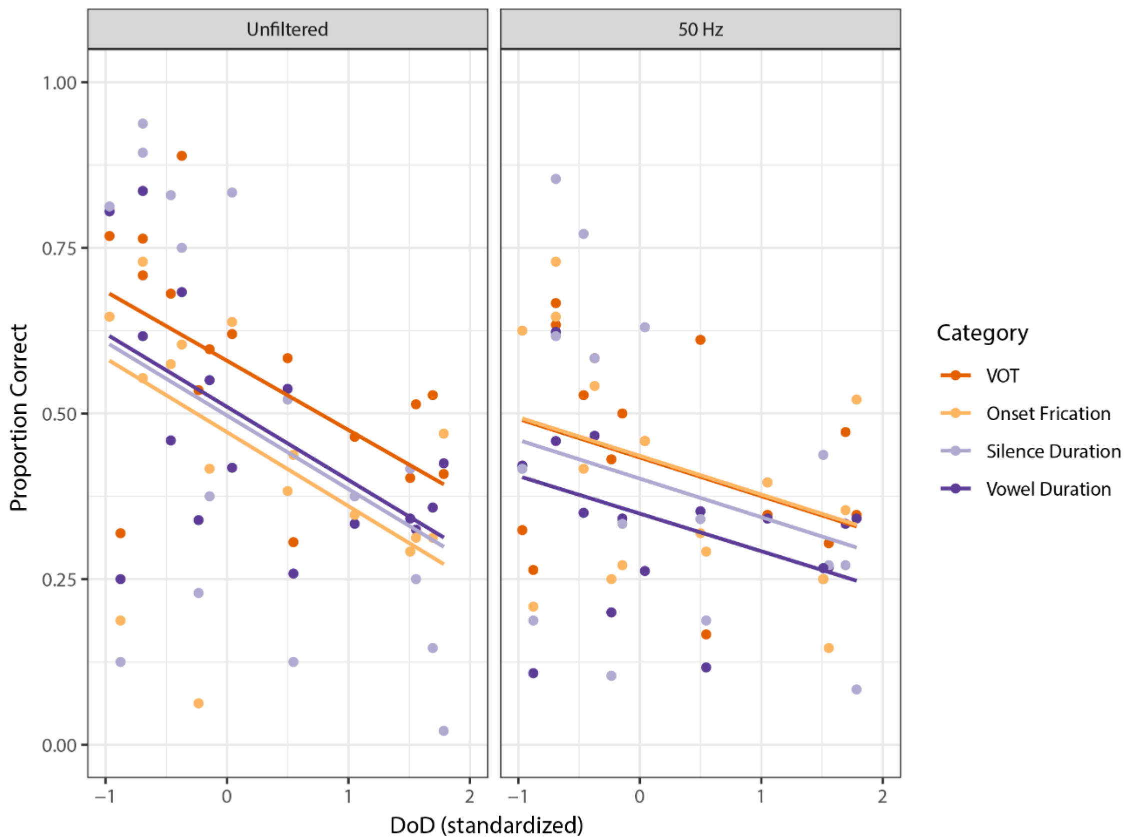


Figure 18. Scatter plot of participants' mean proportion phoneme identification performance in the unfiltered condition (left panel) and the 50-Hz filtering condition (right panel) plotted as a function of DoD (z-scores). The regression lines represent the predicted data fitted to their respective category model.

Cognitive capacity in the domains of speed of processing (Pattern Comparison test), working memory (List Sorting and Picture Sequence tests), and attention (Flanker and Dimensional Change Card Sort test) was evaluated to determine the cognitive variables that might predict phoneme recognition performance. Cognitive variables did not significantly predict performance, and none of the cognitive scores significantly improved model fit for any of the four GLMMs. Table 9 displays a correlation matrix for the cognitive variables and age, DoD, and age at onset of hearing loss. Although none of the cognitive variables contributed to phoneme recognition performance, significant negative correlations were found between age and measures of speed of processing (Pattern Comparison and Card Sort) and attention (Flanker). This finding demonstrated the expected age-related decline in cognitive capacity in these domains (Humes et al., 2006; Park et al., 1996).

Table 9.
Correlation Matrix: Age and Cognitive Measures.

	Age	DoD	Onset	List Sort	Pattern	Pic. Seq.	Flanker	Card Sort
Age	1							
DoD	0.13	1						
Onset	**0.58***	**-0.73****	1					
List Sort	-0.3	**-0.73****	0.39	1				
Pattern	**-0.76****	-0.12	-0.41	0.3	1			
Pic. Seq.	-0.31	0.02	-0.24	0.32	0.15	1		
Flanker	**-0.77****	-0.3	-0.28	**0.49***	**0.66***	0.24	1	
Card Sort	**-0.77****	-0.24	-0.33	0.44	**0.73****	0.32	**0.85****	1

Note. * = p<0.05, ** = p<0.001; DoD = duration of deafness; Pic Seq. = Picture Sequence task

Error patterns.

Error patterns for consonant confusions were evaluated for each participant. Errors were classified as either a Place, Voicing, or Manner error. All of these error types and combinations of error types were possible, given the open-set nature of the response task. Place errors comprised consonant confusions that only differed in the place of articulation, while the voicing and manner of the consonant remained consistent with the target phoneme. Voicing errors comprised consonants that were confused as a voiced phoneme when it was produced as a voiceless phoneme and vice versa. Manner-of-articulation errors comprised confusions in phonemes based on how the airflow was (or was not) obstructed within the mouth/throat, while the place of articulation and voicing characteristics were consistent with the target phoneme. Error patterns were classified as either one of the single error-types, as well as combinations of the three main error types. Thus, a phoneme error could be classified as one of seven error types: (1) Place only, (2) Voicing only, (3) Manner only, (4) Place and Voicing, (5) Place and Manner, (6) Voicing and Manner, and (7) Place, Voicing, and Manner. The majority of the errors that were made were either Place-only errors or a combination of Place and Manner. The distribution of the different types of errors for each consonant category are shown in Table 10. Accurate place-of-articulation recognition relies on mostly spectral cues within the phoneme, including spectral peaks and formant transitions. Accurate manner-of-articulation recognition relies on a combination of both spectral and temporal cues within the signal. Place-only errors, which accounted for 35% of the total number of errors made, were not consistently impacted by age or filter condition. In addition, there was no consistent effect of age for Place-only errors when separated into consonant place-of-articulation categories (e.g., plosives, nasals, fricatives). For the Place and Manner combination errors, which made up 33% of the total number of errors made, no consistent impact of advancing age on the error rates was observed.

Table 10.

Proportion of Error Types for Each Consonant Category.

		VOT		Onset Frication		Silence Duration		Vowel Duration	
Error Type	Description	N Errors	Proportion of Total Errors	N Errors	Proportion of Total Errors	N Errors	Proportion of Total Errors	N Errors	Proportion of Total Errors
1	Place Only	662	0.44	317	0.28	374	0.33	951	0.33
2	Voicing Only	116	0.08	272	0.24	14	0.01	177	0.06
3	Manner Only	61	0.04	26	0.02	64	0.06	240	0.08
4	Place and Voicing	82	0.05	104	0.09	42	0.04	125	0.04
5	Place and Manner	375	0.25	255	0.23	489	0.44	1076	0.37
6	Voicing and Manner	18	0.01	8	0.01	5	0.00	43	0.01
7	Place, Voicing, and Manner	168	0.11	118	0.11	63	0.06	274	0.09
8	Target Phoneme Omitted	30	0.02	16	0.01	71	0.06	28	0.01

Note. Proportion of total errors column represents the proporation of errors out of the total numner of errors made for that contrast category.

Although age was not a significant predictor of phoneme recognition performance, it was of interest to examine if age would predict the amount of temporally based errors, as opposed to spectrally based errors, that were made across all consonant contrasts. A purely temporally based error was defined as a Voicing-only type error in the VOT, Onset Frication, and Vowel Duration categories or a Manner-only error for the fricative/affricate contrast (ʃ-tʃ) in the Silence Duration category. Error rates for these temporally based errors are shown as a function of age in Figure 19. Temporally based errors accounted for approximately 10% of the total errors that were made. There was a trend observed in which the error rate increased with increasing age in both filter conditions, but correlation analyses revealed no significant relationship between error rate and age (Unfiltered: r = 0.30, p = 0.193; 50-Hz filtered: r = 0.18, p = 0.447).

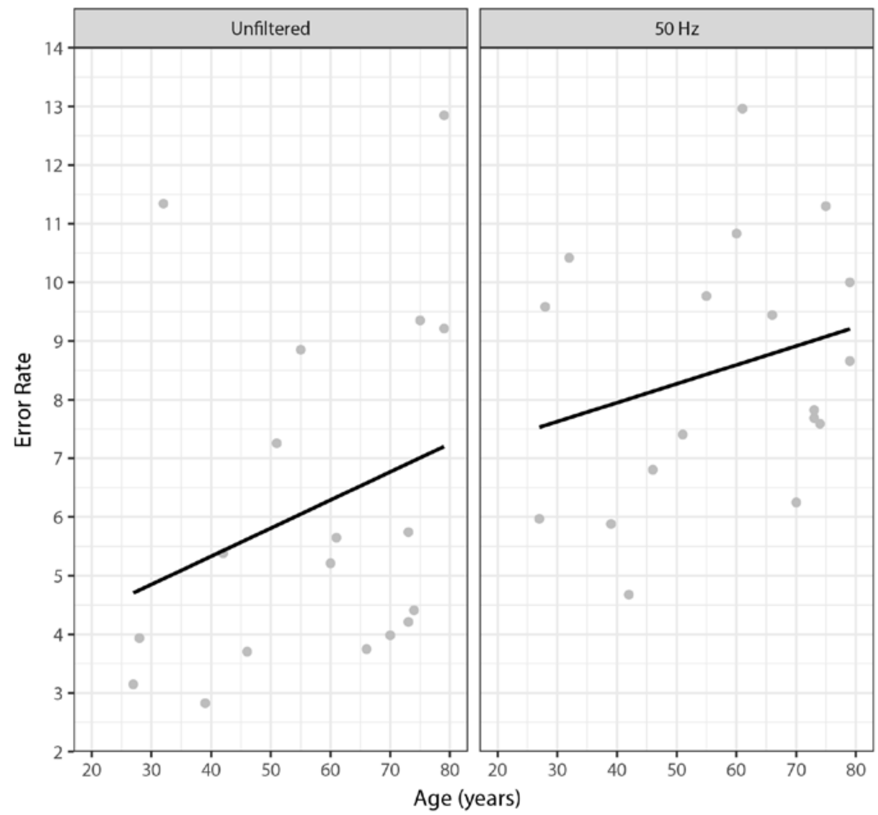


Figure 19. The error rate for temporally based errors for unfiltered stimuli (left panel) and 50 Hz filtered stimuli (right panel) plotted as a function of age. Data points represent each participant's average error rate (# errors divided by total possible) across each contrast category.

Discussion

This study examined the impact of age and other listener-related variables on phoneme recognition performance at a variety of stimulation rates, with and without envelope smearing, in adult CI users. The stimuli were words that varied in discrete temporal cues that signaled consonant identity. Results demonstrated no significant effect of stimulation rate on phoneme recognition. Performance decreased when the envelope modulation frequency was reduced to 50 Hz by envelope filtering. DoD was the only listener-related variable that predicted phoneme recognition performance, with CI users with prolonged DoDs performing significantly worse on this task overall. However, the types of errors that CI users made differed somewhat with age. There was a trend for older participants to exhibit higher error rates for temporally based errors specifically compared to younger participants.

Signal-related factors: Stimulation rate and envelope smearing.

Participants were tested at three stimulation rates: 500, 900, and 1800 pps. Phoneme recognition did not vary significantly as a function of rate at the group level. The effect of stimulation rate was also examined on the individual level, because the impact of stimulation rate is known to vary greatly on an individual basis (e.g., Holden, Skinner, Holden, & Demorest, 2002). Only four participants showed an effect of rate in which performance with a particular rate was either 10 percentage points greater or lower than one or both of the other rates. In these four cases, the “best” rate resulted in between 10-12 percentage point increases in performance compared to the other rates. No consistent pattern was observed regarding which rate resulted in the best performance, nor were older participants more likely to have a “best” rate compared to younger participants. Thus, the hypotheses relating to the effect of stimulation rate for older participants on phoneme recognition were not supported. Overall, stimulation rate did not significantly impact phoneme recognition for this group of participants.

The temporal envelopes of the speech stimuli were smeared using a LPF with a cut-off frequency of 50 Hz to examine the effect of envelope modulation frequency on phoneme recognition. Overall, average performance decreased from 48.2% correct for unfiltered stimuli to 36.1% correct for 50-Hz LPF stimuli. Participants were between 0.49-0.67 times less likely to correctly identify the target phoneme with filtered stimuli compared to unfiltered stimuli. Similar manipulations to spectrally degraded stimuli that mimic CI signal processing (vocoding) show the same decrease in phoneme recognition with reducing the envelope modulation frequency (Schvartz et al., 2008; Xu, Thompson, & Pfingst, 2005). The effect of filtering was not consistent when results were separated into four consonant contrast categories, resulting in many interactions between categories and envelope filtering. To summarize those interactions, the largest relative decrease in performance with envelope filtering compared to unfiltered stimuli was observed for the Vowel Duration category, followed by the VOT category, then the Silence Duration category, and finally the Onset Frication category (Figure 17, p. 103). The discrepancy in the filtering effect between contrast categories may be due to the number of items in each category, with categories with the largest number of items having the largest filtering effects because of the advantage of larger sample sizes. The Vowel Duration category contained responses for the /s-z/, /f-v/, /k-g/, /t-d/, and /p-b/ contrasts in the word-final position. The VOT category contained the /p-b/, /t-d/, and /k-g/ in the word-initial position. The Silence Duration category contained the fricative/affricate contrast /ʃ-tʃ/ in both word positions. The Onset Frication category contained the

/s-z/ and /f-v/ contrasts in the word-initial position. It is important to note that there are other ways in which the stimuli could have been categorized. For example, phoneme recognition can be analyzed with respect to the target phoneme's position within each word, such that recognition could be measured for phonemes in the word-initial position and in the word-final position. For the current study, data were analyzed with respect to the individual contrast categories in an effort to identify age differences that might have been larger in one category compared to another. This is because the duration of the temporal segment that cued consonant identity differed between categories. Acoustic analyses on the same stimuli were reported in Gordon-Salant et al. (2010). The relative difference in VOT between the voiced and voiceless plosives in the VOT category was 80 ms, on average. The difference in the relative onset of voicing following frication between the voiced and voiceless fricatives in the Onset Frication category was 170 ms, on average. Therefore, because the duration of the temporal cue differed substantially between categories, it was of interest to analyze the impact of age for these categories separately.

The envelope smearing condition removed all temporal envelope modulations above a cut-off frequency of 50 Hz. Perceptual studies in acoustic-hearing listeners that limit the temporal modulations within natural and spectrally degraded speech signals have found that consonant recognition performance plateaus when the LPF cut-off frequency exceeds approximately 20-50 Hz, regardless of the amount of spectral degradation (Drullman et al., 1994; Shannon et al., 1995; Van Tasell, Soli, Kirby, & Widin, 1987). However, similar investigations in CI users have found improvements in consonant recognition when the temporal modulation frequency exceeds 50 Hz (Fu & Shannon, 2000). This was also the case in the current study; performance improved by 12 percentage points when the envelope modulation frequency was increased from 50 Hz to ≥200 Hz in the unfiltered condition. This benefit from higher envelope modulation frequencies in CI users' consonant recognition that is not seen in acoustic-hearing listeners could be the result of the inherent spectral differences between acoustic and electric hearing. For acoustic-hearing listeners who are presented with vocoded stimuli, the rapid spectral transitions that cue consonant manner would occur in the correct tonotopic location along the basilar membrane. In CI users, however, the frequency-to-place mismatch would likely map spectral transitions to the incorrect tonotopic location. Therefore, higher-frequency temporal envelope modulations would provide the necessary cues to accurately identify consonant manner. Correct identification of consonant voicing would also benefit from the presence of fundamental frequency information that would be introduced in the temporal envelope with modulation frequencies above 50 Hz.

Listener-related factors: Duration of deafness, age, and cognition.

Biological variables including chronological age, age at onset of deafness, DoD, and cognitive performance were examined as potential predictors of phoneme recognition performance. The only listener-related variable that significantly predicted performance was DoD. With every 1 SD increase in DoD, participants were 0.74 times less likely to correctly identify the target phoneme in any given category or filter condition. DoD is a well-established pre-implantation predictor of CI outcomes. Blamey et al. (2013) reported on a recent update on the factors affecting auditory performance in CI users. DoD was among the top three predictors of post-implantation speech recognition performance along with length of CI experience and age at onset of deafness. For the current study, DoD was calculated as the time between the age at onset of hearing loss to the age of implantation, thus participants with longer DoDs tended to have earlier onsets of hearing loss. There was a significant negative correlation between age at onset of hearing loss and DoD in this group of CI users ($r = -.73$, $p<0.001$), suggesting that these two factors are closely related and are both strong predictors of speech recognition outcomes. Age, on the other hand, was not correlated with DoD in this group of participants ($r = 0.13$, $p = 0.457$), and thus, did not predict phoneme recognition performance in this study (Table 9, p. 107).

When temporally based error rates were examined as a function of age, there was a trend observed in which error rates increased as a function of age (Figure 19, p. 110), but this relationship did not reach statistical significance. This trend was observed for both the envelope filtered and unfiltered stimuli. This trend was not observed, however, for the two most common error types (Place only and Place and Manner combination). If older CI users were experiencing auditory temporal processing deficits, it is possible that age effects would be largest for purely temporal errors in consonant identification. It is unsurprising that the majority of the errors were at least partly, if not all, spectral in nature (i.e., errors comprising a place confusion), because CI users have relatively poor access to spectral cues compared to temporal cues (Winn, Chatterjee, & Idsardi, 2012).

Although the stimuli in the current study were chosen to represent temporal contrasts with the goal of probing potential auditory temporal processing deficits, and thus highlighting potential age effects, age did not significantly predict phoneme recognition performance in this group of CI users. Furthermore, most of the errors that were made were primarily spectral in nature. Therefore, comparisons between the results for error types in the current study and consonant confusions in acoustic-hearing listeners may not be useful. In addition, investigations into acoustic- and electric-hearing phonetic cue-weighting strategies suggests that CI users may be using different perceptual strategies to achieve similar phoneme recognition performance to normal-hearing listeners (Winn et al., 2012).

There was a significant two-way interaction between DoD and envelope filtering. Figure 18 (p. 105) shows the correlations between DoD and consonant recognition performance for the unfiltered and the 50-Hz filtered stimuli. There was a negative correlation in both conditions, suggesting that participants with longer DoDs tended to have poorer phoneme recognition. However, when the final GLMM was releveled to utilize the 50-Hz filtering condition as the reference, the main effect of DoD was no longer significant. This suggested that there was a significant negative correlation between DoD and phoneme recognition performance for the unfiltered stimuli condition (Figure 18, left panel), but not for the 50-Hz filtering condition (Figure 18, right panel). One interpretation of this finding is that participants with shorter DoDs were able to take advantage of the higher-frequency envelope modulations in the unfiltered stimuli to improve their performance, while those with longer DoDs could not. Thus, when stimuli were filtered at 50 Hz, performance did not vary as a function of DoD, because all participants were given stimuli with severely limited temporal information. This resulted in poorer performance overall, regardless of participants' DoD. In other words, when envelope modulations above 50 Hz were removed, the primary limiting factor affecting participants' performance was the stimulus, which was substantially smeared in the temporal domain. But when the stimulus was unfiltered, which allowed envelope modulations up to ~200 Hz to be present in the signal, the primary limiting factor to performance was the participant's hearing history, with participants with longer DoDs performing significantly worse than those with shorter DoDs. This has important clinical implications for cochlear implantees with a long history of auditory deprivation as current clinical sound processing strategies convey higher-frequency envelope modulations likely between 200-400 Hz. Based on these results, it is clear that CI users with longer DoDs were not taking advantage of high-frequency envelope modulations. Future research should investigate strategies for enhancing CI users' access to high-frequency modulations to potentially improve speech recognition.

It was hypothesized that participants' age would interact with envelope filtering, such that younger participants would take advantage of higher-frequency modulations when available while older participants would not be able to benefit from higher-frequency modulations, or at least not to the same degree as their younger counterparts. While there were no significant effects nor interactions of age on phoneme recognition, advancing age and prolonged periods of auditory deprivation can be thought of as having the same effect on the peripheral auditory system. Ultimately, the effect is a reduction in SGCs in the periphery. Prolonged DoDs result in substantial reductions in SGC density (Leake et al., 1999). Likewise, advancing age in animal models also results in widespread reductions in SGCs, even in the absence of hearing loss (Kujawa & Liberman, 2015; Mills, Schmiedt, Schulte, & Dubno, 2006; Sergeyenko et al., 2013). If the same is true in humans, the eventual loss of SGCs with prolonged deafness and/or age has crucial implications for the encoding of temporal envelope cues. Lopez-Poveda (2014) modeled auditory nerve responses with significantly reduced numbers of SGCs and found that the resulting neural response was essentially “undersampled,” in signal processing terms. This “stochastic undersampling” of the temporal envelope could result in poor envelope and/or AM encoding for participants with a limited number of surviving SGCs. In this way, prolonged DoDs and advancing age can both be thought to result in a significant reduction in SGCs in the peripheral auditory system, which could limit participants’ ability to encode rapid envelope modulations that facilitate accurate consonant recognition.

It was also hypothesized that scores on the cognitive measures would reveal age-related declines in the domains of speed of processing, working memory, and attention. Furthermore, it was hypothesized that cognitive capacity would contribute to phoneme recognition ability. While age-related declines were noted for the speed of processing and attention measures (Table 9, p. 107), none of these variables significantly contributed to phoneme recognition performance. The findings of the current study suggest that the strongest subject-level variable that predicted performance was DoD, and not age. Scores for the majority of the cognitive measures were correlated with age, while only one measure (List Sorting score) was significantly correlated with DoD. One potential reason why cognitive variables did not significantly predict performance on this phoneme recognition task is because the cognitive scores were negatively correlated with chronological age, while the phoneme recognition scores were closely related to DoD. In a similar study, Holden et al. (2013) evaluated speech recognition in 114 adult CI users and found that a composite measure of cognition was positively correlated with word recognition scores. However, when controlling for the effect of chronological age on cognitive scores, there was no longer a relationship between speech recognition and cognition. This result suggested that cognitive decline due to aging may have negatively impacted word recognition scores in CI users.

Another potential reason why cognition did not contribute to phoneme recognition scores is the nature of the task. The current study measured phoneme recognition by presenting CVC word stimuli in quiet within sentences without contextual cues and used an immediate recall task. Typically, contributions of cognitive decline to speech recognition measures in acoustic-hearing listeners are observed for sentences or discourse, as well as in conditions that present stimuli in noise (Akeroyd, 2008; Gordon-Salant & Cole, 2016; Schneider & Pichora-Fuller, 2000). In addition, CI users' word recognition ability is highly sensitive to the amount of linguistic context. Older CI users, as well as older acoustic-hearing listeners, glean a larger advantage from the presence of sentence context compared to younger users (Amichetti, Atagi, Kong, & Wingfield, 2018). However, more robust linguistic context increases the number of potential words that could accurately represent the target word. Older adults have more difficulty than younger adults identifying a target word if there are many appropriate alternatives, suggesting an age-related decline in inhibition (Lash, Rogers, Zoller, & Wingfield, 2013). This reduction in inhibition puts older CI users at a disadvantage compared to younger CI users, even when robust linguistic context is available (Amichetti et al., 2018). The current study, however, provided no contextual cues for the CVC word stimuli, which could have reduced the potential impact of cognition on older CI users' performance in this task.

Conclusions

This final study investigated the effect of age, DoD, and cognitive capacity on phoneme recognition performance, at a variety of stimulation rates and envelope modulation frequencies, in adult CI users. It was hypothesized that advancing age would result in poorer phoneme recognition overall, and that younger participants would be able to take advantage of higher-frequency envelope modulations while older participants would not. It was also expected that older participants would perform best with relatively low electrical stimulation rates, whereas younger participants would perform best with higher stimulation rates because they would be able to take advantage of the more rapid envelope sampling that occurs with higher rates. Findings suggested that DoD, rather than age, was the strongest subject-level predictor of phoneme recognition performance. Reducing the envelope modulation frequency to a maximum of 50 Hz significantly reduced performance overall. However, performance in the unfiltered condition was predicted by DoD, with participants having short DoDs performing significantly better than participants with prolonged periods of deafness. This suggested that participants with shorter DoDs were able to take advantage of higher-frequency envelope modulations while participants with longer DoDs could not.

Stimulation rate did not affect phoneme recognition performance. Cognitive variables also did not significantly predict performance on this phoneme recognition task. These findings suggest that DoD strongly predicts phoneme recognition ability in quiet among CI users. Additionally, results suggested that one of the consequences of prolonged deafness may be limited access to higher-frequency temporal envelope modulations above 50 Hz, which is a limitation that negatively impacted phoneme recognition for unfiltered stimuli.

Comprehensive Summary and Discussion

The goal of this research was to identify age-related temporal processing deficits for speech and non-speech signals using different electrical stimulation parameters in adult CI users. While CIs are considered to be the world's most successful neural prostheses (Wilson & Dorman, 2008), performance with a CI is highly variable from person to person (Holden et al., 2013). A prolonged period of auditory deprivation prior to implantation is among the strongest pre-implantation predictors of post-implantation speech recognition performance (Blamey et al., 2013). Chronological age is another predictor of post-implantation CI performance in adults, although the amount of variability in performance accounted for by age is somewhat debated. Three factors were hypothesized to contribute to an age limitation in adult CI users: (1) age-related reductions in peripheral neural survival resulting in a poor electrode-to-neural interface, (2) age-related auditory temporal processing deficits, and (3) age-related declines in cognitive processing ability.

The electrode-to-neural interface is critical to the successful encoding of electrical signals delivered by a CI to the SGCs in the peripheral auditory system. Prolonged DoDs severely impact the peripheral system, resulting in a loss of SGCs (Leake et al., 1999) and altered temporal discharge patterns for electrically stimulated SGCs (Shepherd & Javel, 1997). Aging also causes alterations to SGCs in animal models, ultimately resulting in a significant loss of SGCs in the periphery, even in the absence of hearing loss (Kujawa & Liberman, 2015; Makary et al., 2011). If this is also true in humans, prolonged DoDs and advancing age could both potentially cause a loss of SGCs. Therefore, age was hypothesized to impact the electrode-to-neural interface in the same way that prolonged DoD would be expected to impact the electrode-to-neural interface.

Another factor that was hypothesized to contribute to age limitations in CI performance was age-related central auditory temporal processing deficits. CIs convey sound primarily by delivering the temporal envelope of the signal while spectral cues are limited, which requires CI users to rely on temporal cues to understand speech (Shannon et al., 1995). Therefore, an individual's ability to understand speech received from a CI depends, at least in part, on their ability to effectively process temporal information. Advancing age is associated with temporal processing deficits for a multitude of behavioral psychoacoustic measures (Fitzgibbons & Gordon-Salant, 1994; Snell & Frisina, 2000) and electrophysiological measures in humans (e.g., Leigh-Paffenroth & Fowler, 2006), as well as physiological measurements in animal models (e.g.,Walton et al., 1997). If older CI users are experiencing some degree of age-related temporal processing deficits, it is reasonable to assume that their performance with a CI would be limited compared to their younger counterparts.

Lastly, age-related changes in cognition were hypothesized to also contribute to age limitations in older CI users' speech perception, specifically their phoneme recognition ability that was assessed in Study 3. Because CI-processed speech is severely degraded, successful speech recognition through a CI may require some reliance on cognitive resources. This is because the recognition of degraded signals depends, in part, on a listener's cognitive ability (e.g.,Wingfield & Tun, 2001). Thus, age-related cognitive decline could limit older CI users' ability to effectively decipher the degraded speech signals they receive from their CI.

Direct stimulation procedures were used to test CI users' auditory temporal processing of static and dynamic non-speech signals in two, single-electrode psychoacoustic studies (Studies 1 and 2). Temporal processing was also evaluated for multi-electrode stimulation using speech stimuli in a phoneme recognition task for consonants that varied in discrete temporal cues (Study 3). The contribution of peripheral neural survival to temporal acuity was estimated using ECAP AGFs at the same electrode locations that were tested in Studies 1 and 2. The contribution of cognition to the recognition of temporally contrasting phonemes was evaluated using measures of speed of processing, working memory, and attention in Study 3. In each study, the electrical stimulation parameters were manipulated to identify potential interactions between temporal acuity and the choice of stimulation parameters in older CI users. It was hypothesized that age-related changes to the auditory system, including a presumed reduction in SGCs, and the resulting limitations in temporal processing, would put older CI users at a disadvantage when using the default stimulation settings (e.g., fast electrical stimulation rates). Thus, the electrical stimulation rate was varied in all three studies, and the envelope modulation frequency was varied in Studies 2 and 3, in order to determine if older CI users' performance could be improved given more favorable stimulation conditions.

Study 1 evaluated the effect of age on gap detection ability at multiple electrode locations using a variety of stimulation rates. It was hypothesized that gap detection ability would decline with advancing age due to age-related temporal processing deficits for static, non-speech stimuli. Peripheral neural survival, as measured by ECAP AGFs, was expected to decline with age and was hypothesized to also contribute to gap detection ability above and beyond the effect of age alone. Results for Study 1 suggested that peripheral neural survival was a significant predictor of gap detection ability; electrodes with steeper ECAP AGF slopes tended to exhibit better gap detection thresholds. But this effect depended on the stimulation rate and on the participant's age. At the fastest stimulation rate (4000 pps) for older participants, steeper ECAP slopes were no longer associated with better gap detection thresholds. Initially, this result suggested that peripheral neural survival was the strongest subject-level predictor of gap detection ability, and that age *per se* also contributed to the results beyond what was predicted by ECAP slopes alone. However, ECAP slope and age were negatively correlated, with younger participants exhibiting the steepest ECAP slopes and older participants exhibiting the shallowest slopes. In this way, ECAP and age were not independent of each other. This observation precluded a complete evaluation of the relative contributions of each factor on gap detection ability that were independent of the other.

Study 2 measured the effect of age on AM detection ability at a variety of electrical stimulation rates. It was hypothesized that older participants would demonstrate reduced AM detection ability compared to younger participants, due to auditory temporal processing deficits for dynamic, non-speech stimuli. Performance for electrodes with shallow ECAP slopes did not differ from electrodes with steeper ECAP slopes, and thus, the effect of peripheral neural survival was initially not found to be predictive of AM detection ability. Age, on the other hand, did significantly predict performance, with older participants requiring larger depths of modulation to detect the presence of AM. However, similar to the findings for Study 1, age and ECAP slope were negatively correlated. Younger participants had much steeper ECAP slopes compared to older participants. And thus, the results could not be analyzed to evaluate the relative and independent contributions of age and peripheral neural survival to AM detection ability.

Taken together, the results for Study 1 and Study 2 may seem somewhat contradictory. In Study 1, gap detection ability was primarily predicted by ECAP estimates of peripheral neural survival, with age only contributing to the results within the context of ECAPs and rate. In Study 2, AM detection ability was primarily predicted by age, with no significant differences in performance between electrodes with relatively steep ECAP slopes vs electrodes with relatively shallow ECAP slopes. One interpretation is that these two tasks, one a static measure and one a dynamic (i.e., speech-like modulations) measure, probe different levels of processing for temporal input (Walton, 2010). However, behavioral data from psychoacoustic studies in normal-hearing listeners have also shown that gap detection ability and sensitivity to AM are closely related (Formby & Muir, 1988) and performance on both tasks can be predicted by the same mathematical model (Forrest & Green, 1987). Thus, it is more likely that both factors, ECAPs and age, impacted both measures of temporal processing because those factors were correlated with one another and both represent a proxy for peripheral neural survival (i.e., SGC counts).

It is well-known that auditory deprivation causes widespread loss of SGCs in the periphery. The trajectory for this loss is accelerated when compared to aging ears with no evidence of peripheral pathology (Makary et al., 2011). For ears with acquired sensorineural hearing loss, temporal bone studies have shown greater than a 50% loss in the number of SGCs in cochlear regions with substantial hair cell loss. However, SGC loss is also observed in healthy aging (e.g., ears with no evidence of pathology). Histological studies in normal-hearing human ears have estimated the loss as a result of aging to be between 1,000 and 2,000 SGCs per decade starting at birth (Makary et al., 2011; Otte, Schuknecht, & Kerr, 1978). Regardless of the mechanism responsible for SGC loss, whether it be auditory deprivation or aging, the resulting impact on the electrode-to-neural interface has implications for CI users. Poor electrode-to-neural interfaces are associated with poor gap detection thresholds (Bierer et al., 2015) as well as poor AM detection thresholds (Garadat et al., 2013).

To summarize, results from Studies 1 and 2 suggest that the factors of chronological age and ECAP slope are both representative of peripheral status, with age being an indirect indication of neural survival and ECAP AGFs being a more objective measurement for CI users. Both of these factors significantly impacted auditory temporal processing ability, which confirmed the results from previous studies that showed poorer temporal acuity with poor electrode-to-neural interfaces. Results from Studies 1 and 2 suggest that these two factors should be considered together, rather than as two independent factors, when considering auditory temporal processing ability at the single-electrode level for non-speech stimuli.

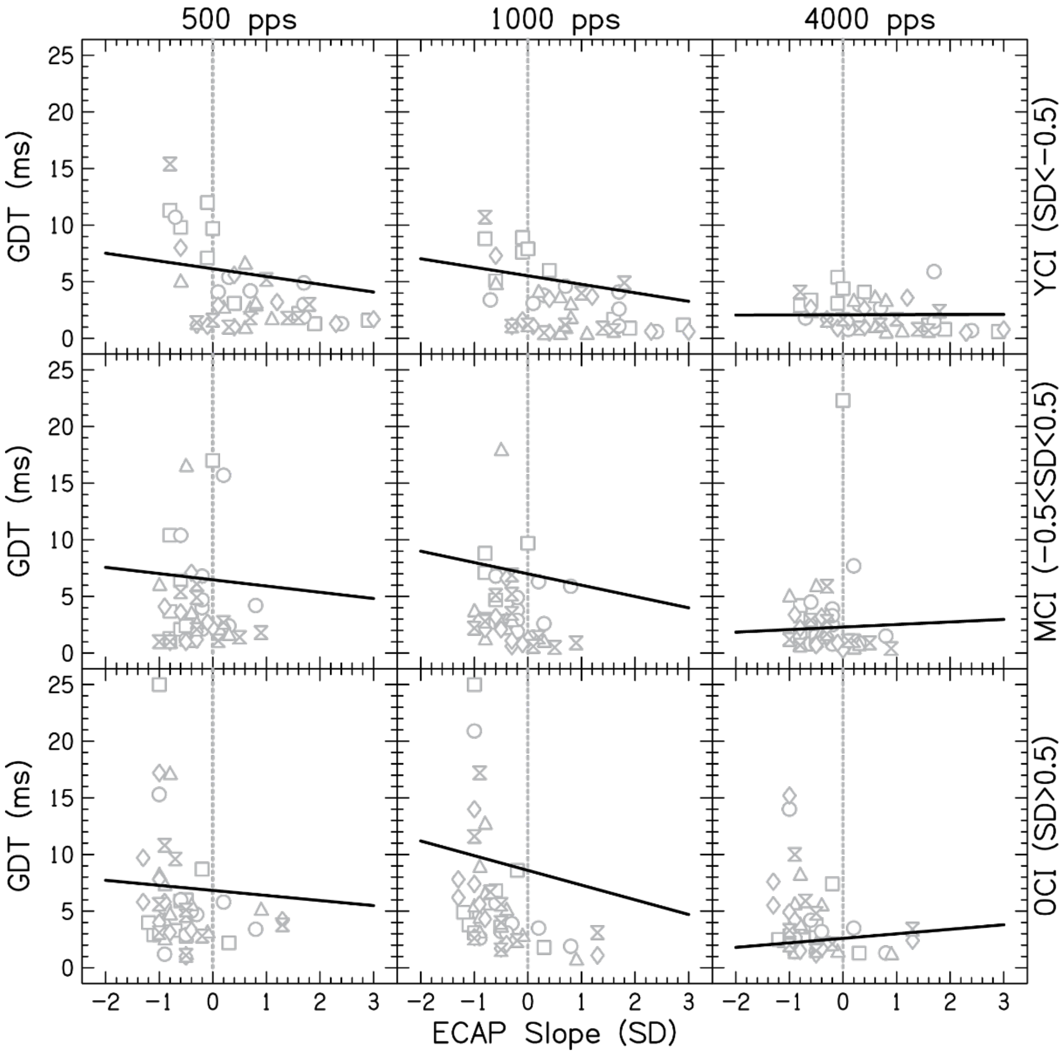
Study 3 investigated the effect of age and cognitive capacity on phoneme recognition performance using different stimulation rates and envelope modulation frequencies. It was hypothesized that advancing age would result in poorer performance overall, and that younger participants would benefit from the higher frequency envelope modulations in the signal while the older participants would not, due to auditory temporal processing deficits in envelope modulation processing. Results showed that DoD was the strongest subject-level predictor of phoneme recognition, with participants with longer DoDs having poorer performance overall. Additionally, DoD interacted with envelope filtering in the same way that was hypothesized for advancing age. Participants with shorter DoDs were able to take advantage of higher-frequency envelope modulations when available while participants with longer DoDs did not.

The results for Study 3 support the conclusions from Studies 1 and 2. Although age and DoD were not correlated in this group of participants tested in Study 3, longer DoDs are presumably indicative of increased SGC loss (Leake et al., 1999). Participants with long DoDs may have obtained poorer phoneme recognition scores because of reduced peripheral neural survival, resulting in poor electrode-to-neural interfaces. Furthermore, the phoneme recognition task that was used in this study proved to be a very difficult task. The average target phoneme recognition scores were approximately 40% correct. The experimental task was also completed using a very limited number of active electrodes (eight), which does not represent a typical clinical CI map. In this way, the task was not a traditional “speech recognition” study with direct clinical relevance. This may explain why cognition did not significantly contribute to phoneme recognition scores in this study. In other words, the maps that were used in this study were quite novel to the participants and did not mimic typical mapping procedures that are used clinically. The use of novel CI maps may be the reason why factors that directly impact peripheral neural survival, rather than cognition, were stronger predictors of phoneme recognition performance.

Parametric variations in the stimulation rate and modulation frequency did not systematically improve older CI users’ performance on these temporal processing tasks compared to younger CI users. On the individual level, however, some participants benefited from one stimulation rate over others in Study 3, but these patterns were not consistent across participants and were not predicted by age or any other factor. This result is consistent with prior studies showing that the effect of parameter changes (e.g., stimulation rate) varies substantially from person to person, without a clear indication of which CI users will benefit from lower rates and which will benefit from higher rates. Results from these studies suggest that parameter optimization is still advantageous on a case-by-case basis, but that parameter changes do not overcome the temporal processing limitations that were displayed by older participants and/or those who likely have poor peripheral neural survival.

Taken together, the findings from these studies clarify the effect of chronological age on CI performance. One major finding is that the changes to the peripheral auditory system that appear to occur with advancing age are similar to the changes that occur as a result of auditory deprivation. Prolonged periods of auditory deprivation can occur in older CI users as well as in younger users with congenital or pre-lingual hearing loss. Another factor that almost always correlates with chronological age is the age at onset of hearing loss. On average, a group of younger CI users will have lost their hearing earlier in life compared to a group of older CI users, at least in today's generation of CI users. This further confounds the comparisons between groups of younger and older CI users. Different methodological strategies for evaluating the potential impact of age that is independent of peripheral status could include studies that match younger and older participants on the basis of objective measurements that probe the electrode-to-neural interface. Overall, the results reported here suggest that CI research should focus less on a single subject-related factor, such as age *per se*, or even DoD, and to instead consider the effect that one or both of those factors have on the peripheral auditory system. Research should focus on mitigating the consequences that those changes can have on the perception of speech signals received from a CI. Furthermore, future studies should expand these findings from non-speech signals and simple words to incorporate more speech materials, including sentence-length stimuli in a variety of listening conditions.

Appendix



Appendix A. GDTs plotted on a linear scale as a function of ECAP slope for the three stimulation rate conditions (columns). Participants were separated into three age groups in order to highlight the interactions between rate, ECAP slope, and chronological age. YCI group (N=9) represents participants with ages ≤-0.5 SD below the mean (≤44 years). MCI group (N=11) represents participants with ages between -0.5-0.5 SD around the mean (45-63 years). OCI group (N=10) represents participants with ages >0.5 SD above the mean (≥64 years).

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