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Research Article

Individual Hearing Outcomes in Cochlear Implant Users Influence Social Engagement and Listening Behavior in Everyday Life

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Purpose: The goal of this study was to assess the listening behavior and social engagement of cochlear implant (CI) users and normal-hearing (NH) adults in daily life and relate these actions to objective hearing outcomes.
Method: Ecological momentary assessments (EMAs) collected using a smartphone app were used to probe patterns of listening behavior in CI users and age-matched NH adults to detect differences in social engagement and listening behavior in daily life. Participants completed very short surveys every 2 hr to provide snapshots of typical, everyday listening and socializing, as well as longer, reflective surveys at the end of the day to assess listening strategies and coping behavior. Speech perception testing, with accompanying ratings of task difficulty, was also performed in a lab setting to uncover possible correlations between objective and subjective listening behavior.
Results: Comparisons between speech intelligibility testing and EMA responses showed poorer performing CI users spending more time at home and less time conversing with others than higher performing CI users and their NH peers. Perception of listening difficulty was also very different for CI users and NH listeners, with CI users reporting little difficulty despite poor speech perception performance. However, both CI users and NH listeners spent most of their time in listening environments they considered "not difficult." CI users also reported using several compensatory listening strategies, such as visual cues, whereas NH listeners did not.
Conclusion: Overall, the data indicate systematic differences between how individual CI users and NH adults navigate and manipulate listening and social environments in everyday life.

Cochlear implants (CIs) have been successful in restoring a sense of hearing for many individuals with profound hearing loss. In addition to an improvement in hearing outcomes, several studies have also shown an increase in overall quality of life postimplantation (e.g., Chung et al., 2012; Crowson et al., 2017; McRackan et al., 2018). A 2015 study (Mäki-Torkko et al., 2015) comparing experiences of 101 CI users and their significant others pre- and postimplantation describes the two experiences as living in two different worlds, with postimplantation associated with increases in normality, autonomy, and social engagement. This increase in quality of life is not altogether surprising, given the severe level of hearing loss required to qualify to receive a CI and the ability of the device to provide some auditory input for most users. However, the relative social engagement of CI users compared to their normal-hearing (NH) peers is much less understood and clear-cut.

Focus groups of CI users interviewed by Hughes et al. (2018) on topics related to listening effort, social engagement, and overall quality of life highlighted ongoing social difficulties postimplantation. One participant described feeling isolated in group settings due to the increased effort and time needed to listen and assimilate to the rapid, continuous nature of dialogue. The extra time needed to process and understand what is being heard through CIs also often limited the ability of users to actively contribute to conversations, with many finding themselves more in an "observer" role than truly socially engaged (Hughes et al., 2018). The degraded speech signal

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delivered by CIs leads to a complex social landscape for CI users where assessing their own ability to hear successfully in a given environment, the cognitive demands of listening, the level of fatigue and anxiety associated with social engagement, and the level of social support contribute to the eventual decision of how to proceed in a given social situation (Pichora-Fuller, 2016).

Though relatively little is known about the association between hearing outcomes of CI users and social engagement postimplantation, many studies have shown hearing loss, in general, to be associated with social isolation, depression, and cognitive decline in adults (e.g., Chia et al., 2007; Kim et al., 2017; Lin et al., 2013; Mick et al., 2014; Pronk et al., 2011). In a cross-sectional and longitudinal study of 767 older adults living in community dwellings, Mikkola et al. (2016) found that fully mobile adults with hearing loss spent significantly less time outside the home and were 3 times more likely to withdraw from leisure activities than equally mobile adults with good hearing. Severe hearing loss was also found to significantly increase the risk of depression in 30,000 patients followed by Kim et al. (2017) for a period of 11 years, regardless of age. Since depression and social withdrawal often precede declines in overall health and quality of life (Shankar et al., 2017; Stubbs et al., 2017), researchers and clinicians have long hoped that hearing interventions and treatment, with devices such as hearing aids and CIs, may be able to mitigate this downward social and physical health trend.

Many studies have shown increases in cognitive health (Dawes et al., 2015), listening ability, and overall health outcomes with the adoption of hearing aids (Kitterick & Ferguson, 2018). A recent study looking at the effects of auditory rehabilitation in 125 adults with hearing loss reported patients making gains in hearing outcomes, short- and long-term memory, and reduced depression after receiving various hearing interventions (Castiglione et al., 2016). Although these findings are encouraging, the causal link between hearing aids and improvements in quality of life is not always straightforward. The vast majority of studies looking at this relationship have analyzed changes in adults with hearing loss who have willingly chosen to purchase hearing aids and regularly participate in auditory rehabilitation. Though these individuals may see improvements in quality of life and hearing outcomes, it may simply be because those who are proactive about managing health problems have other innate qualities, such as perseverance or a positive outlook, that mediate these gains.

Given the wide range of hearing outcomes for individual CI users (Hast et al., 2015; Lenarz et al., 2012; Mahmoud & Ruckenstein, 2014), understanding the connection between speech understanding and social engagement is crucial. Since many adult CI users receive little or no formal training or rehabilitation with the device, it could be that individuals who seek out social activities more frequently achieve better speech understanding, facilitated by practice in difficult environments. On the other hand, differences in signal quality and speech perception abilities across users may cause those who struggle with the device initially to withdraw socially. CI users in the Hughes et al. (2018) study describe having a "finite amount of energy […] that can be used up very quickly," depending on other health ailments, work commitments, and social engagements on any given day. Thus, if a CI user feels the need to prioritize work or struggles with other energy-draining health complications, listening rehabilitation and social engagement might not get as much attention and may suffer, as a result. On the other hand, if a CI user is driven by the need for social connectedness (Hughes et al., 2018), the consistent act of participating in dynamic and difficult social situations may bolster speech understanding with the device.

In addition, differences in the "perception" of listening difficulty by individual CI users in various environments and social situations may influence social engagement, as well. A study by Sato et al. (2012) comparing word intelligibility and ratings of listening difficulty found differences in rating behavior between younger and older adults, with older adults rating the same level of speech understanding as less difficult than younger adults. Since many older adults in the study had hearing loss, the effect could be due to age, hearing status, or a combination of the two. Speech intelligibility has traditionally been viewed as a proxy for subjective phenomena, such as listening difficulty or effort, but a recent study by Winn and Teece (2021) highlights the dissociation between listening effort and speech understanding in several speech contexts. It remains an open question how and to what extent listening effort and the perception of listening difficulty impact social engagement and hearing outcomes in CI users.

A logical first step to better understand the complex relationship between hearing outcomes and social engagement in CI users would seem to be to establish that there is evidence for such an association. Therefore, the purpose of this study was to answer two basic questions: (a) Are individuals who achieve better hearing outcomes with CIs more socially engaged than those who achieve poorer outcomes? (b) Are CI users as a group less socially engaged than their NH peers? We assessed hearing outcomes by measuring speech understanding of complex, multitalker sentences, presented in varying levels of background noise, in postlingual, adult CI users and age-matched NH listeners. We also asked participants to rate the difficulty of understanding these sentences in the lab and used these ratings as a benchmark when assessing ratings of speech understanding difficulty in actual social environments. Social engagement of CI users and NH adults was measured using ecological momentary assessments (EMAs). Two different surveys, assessing social engagement and listening behavior, were completed by participants via a smartphone app during the course of their everyday lives. We predicted that NH participants would be more socially engaged than CI users and that poorer performing CI users would be even less socially active than better performing CI users.

Experiment 1: Speech Perception and Difficulty Ratings

Method

Participants

A total of 18 postlingual, adult CI users (14 women and four men), ranging in age from 37 to 79 years (*M* = 62.3 years, *SD* = 9.5), participated. All CI users had at least 2 years of CI use, with experience ranging between 2 and 23 years (*M* = 11.9 years, *SD* = 6.2). The duration of hearing loss prior to implantation varied between CI users from less than a year to 33 years (*M* = 11 years, *SD* = 10.5). Fifteen of the CI users used Advanced Bionics devices, two used MED-EL devices, and one used a Cochlear device. Eleven of the CI users were bilateral users, four were unilateral users, and three were bimodal users (one CI and one hearing aid). A group of 18 NH adults (12 women and six men), age-matched on a one-to-one basis to the CI group with ages ranging from 39 to 77 years (*M* = 61.6 years, *SD* = 8.5), also participated. All participants were native English speakers, with the exception of one CI user and one NH participant, both of whom learned and spoke English regularly at a very young age. Normal hearing for the age-matched listeners was defined as having pure-tone audiometric thresholds of less than 20 dB HL at all octave frequencies between 250 and 2000 Hz and no more than 30 dB HL at 4000 and 6000 Hz, with no reported history of hearing disorders. Since close age matching with the CI group was a priority, this audiometric criterion was a compromise that allowed us to successfully recruit older participants with relatively normal hearing. The average threshold for age-matched listeners at 8000 Hz was 18 dB HL (*SD* = 13), with individual thresholds ranging from 0 to 45 dB HL.

All experimental protocols were approved by the institutional review board of the University of Minnesota, and all listeners provided informed written consent prior to participating. The same 36 participants completed all experiments in this study.

Stimuli and Materials

The speech materials were sentences taken from Lists 21–30 from the PRESTO (Perceptually Robust English Sentence Test Open-set) speech corpus (Gilbert et al., 2013), recorded by male talkers with eight different American regional dialects. Each list contained nine sentences, with between three and six key words per sentence. These sentences were used because each list contains a variety of sentence structures, sentence lengths, vocabulary, talkers, and dialects and thus closely resemble speech encountered in the everyday lives of CI users. The sentences were presented in quiet and in Gaussian noise, spectrally shaped to match the long-term spectrum of the speech corpus. The noise was gated on 1 s before the beginning of each sentence and gated off 1 s after the end of each sentence. Five signal-to-noise ratios (SNRs) were selected to reflect a range of noise levels typical of daily listening situations. The same SNRs (0, 5, 10, 15, and quiet) were used for both CI users and NH listeners to facilitate direct comparisons of both speech perception and difficulty ratings between groups.

Subjective difficulty ratings were completed after each block of sentences and recorded by having participants circle their chosen rating on a paper form. The rating scale had four options, which were "not difficult," "somewhat difficult," "difficult," and "very difficult."

Procedure

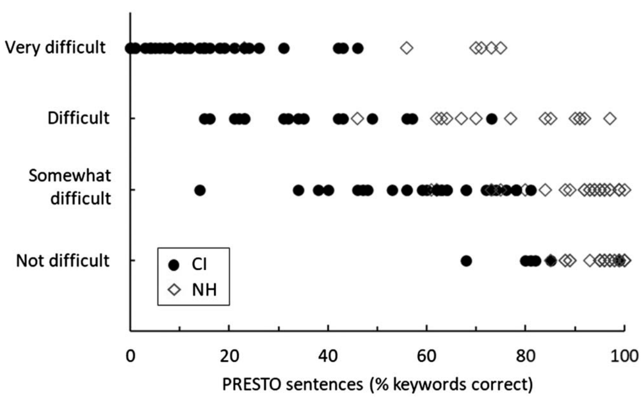
The stimuli were generated using MATLAB and converted via a 24-bit digital-to-analog converter (L22, Lynx Studio) at a sampling rate of 22050 Hz. The sentences were presented in a single-walled, sound-attenuating booth located in a quiet room via an amplifier and a single loudspeaker, placed approximately 1 m from the listener at 0° azimuth.

Listeners responded to sentences by typing what they heard on a computer keyboard. Participants were encouraged to guess individual words, even if they had not heard or understood the entire sentence. Instructions were given orally, and participants were asked if they had any questions about procedures before beginning the task. Sentences were scored for key words correct as a proportion of the total number of key words presented. Initial scoring was automatic, with each error then checked manually for potential spelling errors or homophones (e.g., "wait" and "weight"), which were marked as correct. Two lists of nine sentences each were completed for each SNR tested and randomized across participants. Lists for each SNR were blocked, and the order of blocks was also randomized. After the completion of each block, participants were instructed to give a difficulty rating based on how difficult they felt it was to understand speech within a given block.

Results

The proportion of correct key words for PRESTO sentences at all SNRs tested and corresponding difficulty ratings is shown for individual CI users and age-matched NH listeners in Figure 1. One interesting finding is the extent to which the perception of difficulty varies across individuals as a function of speech understanding. For example, one CI user rated a block in which she understood 14% of key words in sentences as "somewhat difficult," whereas an age-matched NH listener gave the same difficulty rating for a block in which she understood 100% of key words. Among CI users, the rating "somewhat difficult" was assigned to intelligibility scores ranging from 14% to 81%, and scores corresponding to the "difficult" rating ranged from 15% to 73%. In general, CI users were more likely to rate a given level of speech understanding as less difficult than NH listeners at a similar level of speech understanding. Put another way, the average speech perception score corresponding to a given rating was much poorer for CI users as a group than NH listeners. This is more clearly demonstrated in Figure 2A where average speech perception performance is plotted as a function of difficulty rating for each group. Overall, NH listeners were much less tolerant of any decrease in intelligibility, often giving a rating of "somewhat difficult" or "difficult" as soon as just a handful

Figure 1. Speech perception for cochlear implant (CI) users and age-matched normal-hearing (NH) listeners. Percent correct for key words in PRESTO (Perceptually Robust English Sentence Test Open-set) sentences is plotted as a function of difficulty rating for individual participants. Data for individual CI users and age-matched NH listeners are represented by filled circles and open diamonds, respectively.



of words were not perceived clearly. In contrast, performance for CI users had to decrease much more significantly to render a rating of "somewhat difficult" or "difficult."

A multinomial regression model showed a significant difference in rating behavior between groups ($p < .001$), with CI users rating poorer speech understanding as less difficult than their NH peers. This difference is especially stark for the rating of "very difficult," where NH listeners report average speech understanding of 69% as "very difficult," but CI users only assign this rating if performance drops to 14%, on average. In addition, relatively small drops in speech understanding (9%) corresponded to an increase in difficulty rating for NH listeners, whereas CI users tolerated much bigger dips in performance (23%) before assigning a different rating. It is also important to note that the frequency of selecting a given rating differed between the two groups. As shown in Figure 2B, NH listeners selected the rating "not difficult" significantly more often than CI users ($p < .001$), and CI users selected "very difficult" significantly more often than NH listeners ($p < .001$). This difference is due, at least in part, to the fact that overall speech understanding was significantly poorer for the CI group than for the NH group at all SNRs tested ($p < .001$). Taken together, these results indicate that CI users as a group underrate difficulty compared to NH listeners, even though overall performance for CI users is poorer.

CI users were also less able to tolerate background noise, as overall performance was poorer and difficulty rating was higher compared to NH listeners at the same SNR. This can most clearly be seen in Figure 3 where rating behavior for participants in each group is compared directly, as a function of SNR. To give an example, average speech understanding for the NH group at an SNR of 5 dB was 91% and rated as "somewhat difficult" by 13 out of 18 listeners, whereas speech understanding for the CI group was 28% and rated as "very difficult" by 11 out of 18 listeners, at the same SNR. This finding, in particular, has implications for speech understanding and social interactions in more realistic environments, which is explored further in Experiment 2.

Experiment 2: Social Engagement and Listening Strategies as Assessed by EMAs

Method

Participants

The same 36 participants (18 CI users and 18 age-matched NH listeners) who completed Experiment 1 participated in this experiment.

Figure 2. Average speech perception performance and number of responses for ratings of speech understanding difficulty (not difficult, somewhat difficult, difficult, and very difficult) for PRESTO (Perceptually Robust English Sentence Test Open-set) sentences. (A) Average speech perception for each rating. (B) Total number of times each rating was selected. Results for the cochlear implant (CI) and age-matched normal-hearing (NH) groups are shown by black and white bars, respectively.

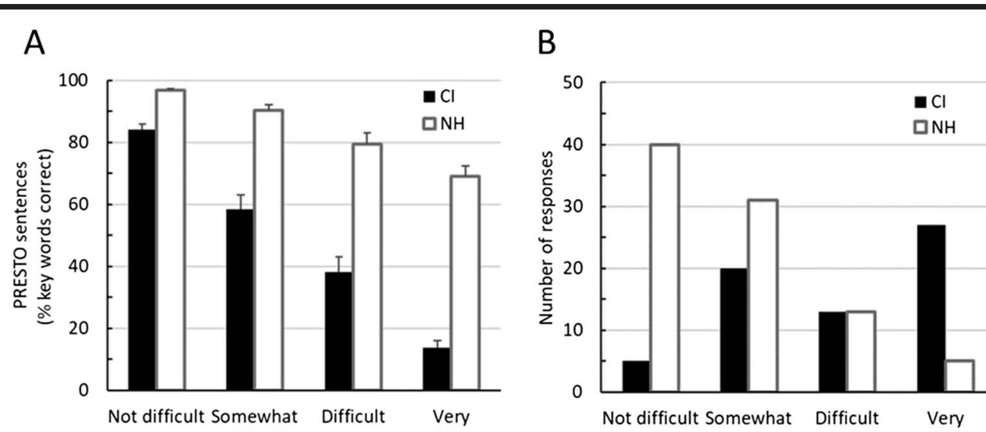
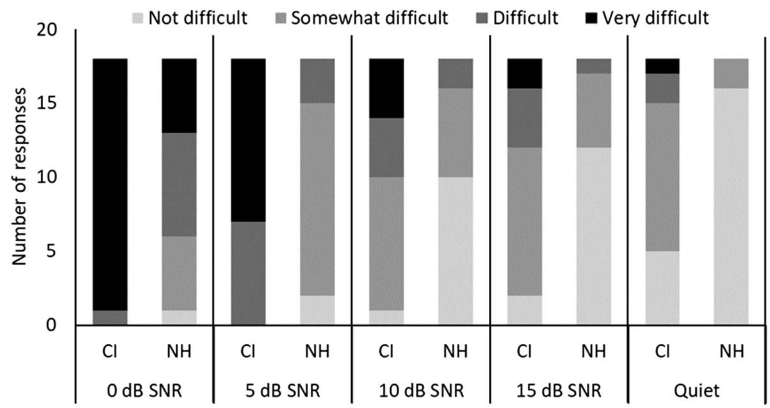


Figure 3. Ratings of speech understanding difficulty for cochlear implant (CI) users and age-matched normal-hearing (NH) listeners at each signal-to-noise ratio (SNR) tested (0, 5, 10, 15, and quiet). The number of participants who selected a given difficulty rating (not difficult, somewhat difficult, difficult, and very difficult) is shown by bars of varying shades of gray, with darker bars indicating more difficulty.



Stimuli and Materials

Participants completed one short and one longer survey multiple times over a 2-week period using a smartphone app called Expimetrics. All data were collected prior to the onset of the COVID-19 pandemic. The questions and response options for the short survey completed by CI users are shown in Table 1. NH listeners provided responses for the first five questions of this survey, as well as an additional question asking whether they were wearing earbuds or headphones at the time of survey completion. This survey was meant to provide a snapshot of various social and listening environments participants found themselves in on a daily basis, and participants provided in-the-moment responses about their activities.

A second, longer survey was also administered, and participants answered questions in the evening, reflecting on the entirety of the day. The purpose of this survey was to probe attitudes and feelings of participants that may have influenced their social and listening behavior throughout the day. Some of these questions were modified from the Cochlear Implant Quality of Life Item Bank (McRackan et al., 2019), and others were created by the authors. A sample of the 28 questions and response options for this survey are shown in Table 2. Questions relating specifically to difficulties due to hearing loss were modified or removed from surveys completed by NH listeners, but there was still a significant overlap in questions completed by both groups of participants to facilitate comparative analysis.

Participants received and completed both surveys on a smartphone app called Expimetrics (now ExpiWell), which is an integrated platform for building, scheduling, and tracking surveys across mobile devices, developed by Dr. Louis Tay, an assistant professor of industrial organizational psychology at Purdue University. All participants downloaded the app free of charge on their personal smartphones. An example of how the questions appeared on participant smartphones via the app is shown in Figure 4. Prior to downloading the app and starting the experiment, a schedule of the dates and times each participant would receive notifications (via the app) to complete surveys was created by the authors on the Expimetrics web platform. All participants were prompted to complete the same number of surveys on the same days of the week, but since participants did not all start the experiment on the same day, the actual calendar dates of the experiment varied across participants. Holiday weeks (i.e., Thanksgiving, Christmas, and New Year) were avoided to prevent the skewing of social engagement data between participants. To facilitate ease of data collection and analysis, individual survey schedules were created for each participant, which corresponded to a unique project code generated by the Expimetrics software. After downloading the Expimetrics app, each participant entered their participant-specific project code into the app, which linked the survey schedule with the participant's smartphone. The "Settings" menu on each participant's smartphone was also checked to ensure that notifications to complete surveys, generated via the app, would be received throughout the experiment.

All data collected from participant smartphones could be viewed in real time (by the authors) on the Expimetrics web platform. The authors monitored the responsiveness of participants to scheduled surveys via the web portal to ensure adequate participation and detect technical issues that might be preventing participants from responding via the app. A few participants required further instruction on how to navigate the app and survey notifications, but these issues were remedied without significant loss of data. All participants were required to complete at least 30 short surveys and two reflective surveys for their data to be included in analysis. Two participants who completed less than 30 short surveys after the 2-week experimental period were able to complete the required amount of surveys after authors scheduled two additional days of survey notifications be sent to their phones. Upon completion of the experiment, each participant's response data were downloaded from the

Table 1. Questions and response options for cochlear implant users completing a short survey administered via the Expimetrics smartphone app.

Q1: Describe the setting you are in RIGHT NOW (check all that apply):
Home
Work
Leisure environment
In transit
Indoors
Outdoors
Q2: Choose the option that best describes the social setting you are in RIGHT NOW:
I am alone/doing something independently.
I am interacting with one other person.
I am interacting with multiple people.
I am around people but not engaging with them.
Q3: Choose the option that best describes what you are listening to RIGHT NOW:
I am not actively listening to anything right now.
I am participating in conversation.
I am listening to some type of media.
I am listening to a live performer/speaker.
Q4: How difficult is it for you to hear what you are listening to RIGHT NOW?
Not difficult
Somewhat difficult
Difficult
Very difficult
Q5: How much background sound is in your environment RIGHT NOW?
Very little background sound
A moderate level of background sound
A high level of background sound
A very high level of background sound
Q6: How many cochlear implant processors are you wearing RIGHT NOW?
2
1
0
Q7: Are you using any other assistive listening devices RIGHT NOW? (e.g., direct audio cable, Mini Mic, and headphones)
Yes
No

Note. Normal-hearing listeners completed the first five questions of this survey, as well as an additional question asking whether or not they were wearing earbuds at the time of survey completion.

Expimetrics web portal into an Excel spreadsheet and then imported into MATLAB for further analysis.

Procedure

Participants completed this experiment over a 2-week period, beginning and ending with a visit to the lab. During the initial lab visit, the Expimetrics app was downloaded on participants' personal phones, and each unique project code was entered into the app, which linked a schedule of survey times and dates to each participant's phone. Participants were told that they would be receiving notifications to complete short surveys on their phone several times a day and on multiple days over a 2-week period, beginning the following day. Participants were also informed that they would not receive surveys every day, but they need to be mindful about keeping their phones on their person throughout the day so as not to miss notifications for surveys. The exact days and times of surveys were not given to participants to ensure participants did not alter their regular daily behavior during the study period.

Each participant received notifications to complete surveys on 8 days (four weekdays and four weekend days) during the study period. On each of these 8 days, participants received eight notifications to complete the short survey, every 2 hr starting at 7:00 a.m. and ending at 9:00 p.m. Participants had an hour window in which to complete each survey and received a reminder to complete the survey 15 min after the initial notification. On four of the eight "study days," participants also received a notification at 8:00 p.m. to complete the longer, more reflective survey. Participants had a 2-hr window in which to complete this survey and received a reminder to complete the survey 15 min after the initial notification. After the 2-week study period, participants returned to the lab to receive a $50 payment for participation in the study and were informed that they could remove the app from their phone, if desired.

Statistical Analysis

All survey questions discussed in the Results section were analyzed using a one-way analysis of variance, with response options as within-subject dependent variables and group as a between-subjects factor, unless otherwise stated. Differences across response options were not tested due to the number of possible comparisons and our focus on assessing differences in response behavior between groups. A p-value criterion of .05 was used to assess statistical significance. All statistical tests used to analyze results from Experiment 2 were performed using IBM SPSS Statistics software.

Results

In-the-Moment Survey Responses

The mean completion rate for the in-the-moment surveys was 72% (46/64 surveys, $SD = 9.8$) for the CI group and 79% (51/64 surveys, $SD = 7.6$) for the NH group. Survey responses were normalized for each individual participant (relative to the number of surveys completed) before being included in further analysis.

The average percentage of time each response option was selected, for the first five questions of the in-the-moment survey, is shown in Figures 5–9. The CI group was split into two groups of nine users each, based on average speech perception scores from Experiment 1. Average speech understanding for the "good CI users" was greater than 40% across all SNRs tested (0, 5, 10, 15, and quiet), and "poor CI users" had average scores below 40%. There was a natural split in performance at 40%, with average performance for the good and poor CI subgroups being 56% ($SD = 7.3$) and 24% ($SD = 11.2$), respectively. There was no significant difference in age between the two groups ($p = .776$).

Figure 5 shows individual response data for the first question of the survey, which asked participants to describe

Table 2. A sample of questions and response options for the longer, reflective survey completed by participants in the evening on four different days over a 2-week period.

Today I found it difficult to talk with staff in places such as shops, cases, or banks.
Not at all
Once or twice
Multiple times
N/A
How much does mishearing or not hearing information when interacting with strangers bother you?
It's not a big deal.
It bothers me a little.
It bothers me quite a bit.
It bothers me a lot.
Today I found it difficult to actively participate in casual conversation.
Not at all
Once or twice
Multiple times
N/A
Today I felt anxious because of my inability to hear clearly.
Not at all
Once or twice
Multiple times
N/A
Today I said the wrong thing in conversation after mishearing what was said and felt embarrassed.
Not at all
Once or twice
Multiple times
N/A
Today I am mentally and/or physically tired from having to listen a lot.
Not at all
Somewhat tired
Very tired
I didn't actively listen much today.
Today I used the following strategies to help me hear (check all that apply):
Watched mouth movements and facial expressions
Repositioned my body closer or farther from the person speaking
Moved objects (furniture, etc.) in my environment
Adjusted the lighting
Selectively conversed with people who had clearer, louder voices
None of the above
Today when I couldn't hear what was being said, I MOST OFTEN responded by:
Asking someone to repeat themselves
Focusing on piecing together what I heard
Pretending to hear what was said by smiling or nodding
Withdrawing from the conversation
I heard everything that was spoken to me today.
Today I put effort into listening, even when it was difficult, because (check all that apply):
What was being said was important.
I wanted to feel connected to others socially.
I felt social pressure to maintain appearances.
I didn't put effort into listening when it was difficult.
Other
Today I stopped trying to listen to something because (check all that apply):
The background sound was too loud.
The person talking was mumbling.
The person talking was speaking too softly.
The person talking had a different accent.
What was being said wasn't important.
I was tired.
I never stopped trying to listen to something.
Other
Describe the MOST difficult listening situation you encountered today.
Describe the LEAST difficult listening situation you encountered today.

Note. N/A = not applicable.

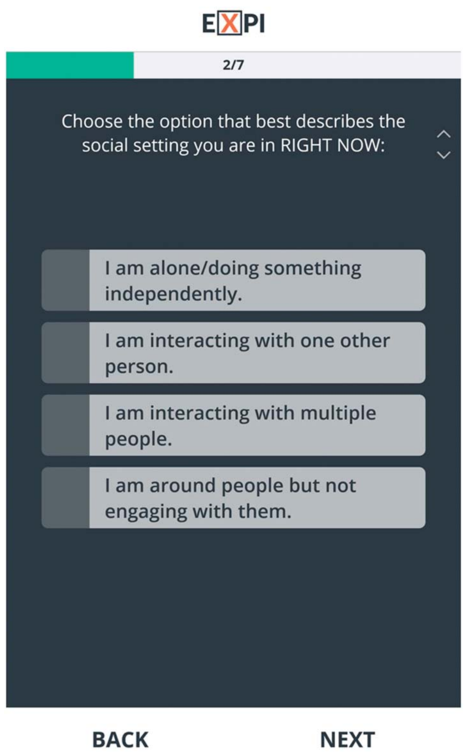
the setting they were in at the time they completed the survey. Participants were allowed to pick more than one response option for this question. In general, all groups of participants spent more time at home than at work and more time indoors than outdoors. Since many participants were not employed, due to age, retirement, or hearing status, they were more often at home than in any other environment. The proportion of participants not working or retired was 44% for the NH and good CI groups and 56% for the group of poor CI users. The average amount of time participants reported being indoors differed between groups, but upon inspection of individual responses, often times participants would indicate they were at home but fail to report whether they were indoors or outdoors. Thus, group differences in the average time spent indoors were not analyzed in further detail.

One interesting finding was that poor CI users spent significantly more time at home than both good CI users (p = .032) and their NH peers (p = .035). Poor CI users also spent significantly less time in transit than good CI users (p = .003) and NH listeners (p = .025). Taken together, these results may indicate a hesitancy for CI users with poorer hearing outcomes to interact with the greater outside world in daily life.

Social engagement was assessed more directly in the second question of the in-the-moment survey, shown in Figure 6, which asked participants to describe the social setting they were in at the time of the survey. On average, NH participants spent 45% of their time alone or doing something independently and 55% of their time either interacting with or around other people. In contrast, poor CI users were alone 60% of the time and only interacting or around others about 40% of the time, on average. Good CI users were somewhere in the middle, reporting being alone 50% of the time and with others 50% of the time. Among CI users, good and poor performers spent about the same amount of time interacting with one other person (27%), but poor performers spent less time interacting with multiple people (12%) than good performers (20%), though this difference was not significant. Poor performers also spent significantly less time around other people but not engaging (2%) than their NH peers (8%, p = .025).

Figure 7 shows results from a question probing listening behavior in the daily life of participants, and although there are no significant differences in responses between groups, trends in listening behavior are in line with previous questions indicating less engagement among poor CI users.

Figure 4. Display of a sample survey question on the Expimetrics smartphone app used in Experiment 2.



On average, poor CI users spent more time not actively listening (42%) than good CI users (39%) and also less time participating in conversation (27% vs. 39%). Compared to NH participants, both groups of CI users spent more time not actively listening to anything and less time listening to a live performer or speaker.

Figures 8 and 9 show responses to survey questions asking about the perceived difficulty of understanding speech and the level of background sound in the everyday environments of participants. Not surprisingly, NH participants reported having no difficulty understanding speech 91% of the time and speech being somewhat difficult to understand 8% of the time, on average. Poor-performing CI users reported understanding speech in their environment as "not difficult" significantly less of the time (p = .008) and "somewhat difficult" significantly more of the time (p = .011) than their NH peers. Good CI users again fell between poor CI users and NH listeners when reporting perceived difficulty in understanding speech. Participants in all groups seem to avoid environments where speech is difficult or very difficult to understand, with NH listeners, good CI users, and poor CI users spending 1%, 2%, and 4% in these environments, respectively. Though it should be noted that the types of environments and social settings that would be perceived as difficult, as well as the ways in which listening difficulty is perceived, vary between groups (see Experiment 1).

In terms of level of background sound in everyday environments, there were no significant differences between groups. In general, all groups spent more time in environments with very little (NH: 66%, good CI users: 69%, poor CI users: 76%) or moderate (NH: 28%, good CI users: 24%, poor CI users: 21%) levels of background sound than environments with high (NH: 5%, good CI users: 6%, poor CI users: 3%) or very high (NH: 1%, good CI users: 1%, poor CI users: 0%) levels of background sound.

Question 6 of the in-the-moment survey was asked only of CI users as it probed the number of processors participants were wearing at the time of the survey. In general, unilateral CI users reported wearing their processor the vast majority of the time (95%), and bilateral users most often wore both processors (72%). However, 28% of the time, bilateral users wore only one (18%) or neither (10%) of their

Figure 5. Individual response data for normal-hearing (NH) listeners, good cochlear implant (CI) users, and poor CI users in response to the prompt, "Describe the setting you are in RIGHT NOW (check all that apply)."

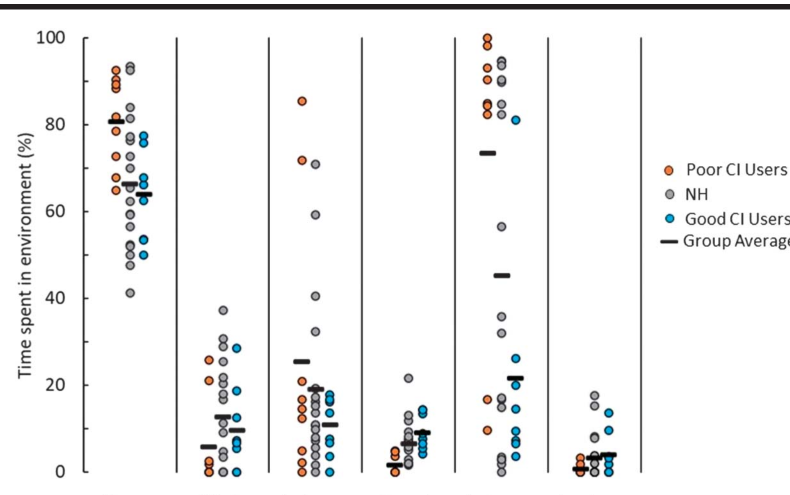
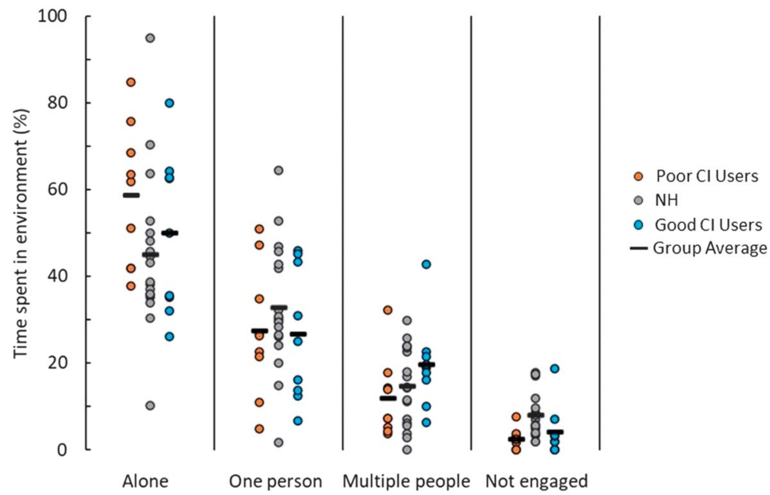


Figure 6. Individual response data for normal-hearing (NH) listeners, good cochlear implant (CI) users, and poor CI users in response to the prompt, "Choose the option that best describes the social setting you are in RIGHT NOW."



processors. Notably, there were no significant differences in device usage between good and poor CI users, indicating that poorer hearing outcomes are not necessarily a result of less time wearing the processors themselves.

The final question of the in-the-moment survey asked CI users to report whether or not they were using assistive listening devices and NH listeners to report whether or not they were wearing headphones or earbuds at the time of the survey. Though headphone or earbud use in NH participants is not a direct proxy for the use of assistive listening devices among CI users, it may serve as a benchmark for the level of interaction with listening-specific technology for this demographic. Overall, the use of assistive technology among CI users was very low, with good and poor CI users utilizing assistive listening devices 2% and 8% of the time, respectively. The use of headphones or earbuds was also very rare among NH listeners, who reported wearing them just 1% of the time, on average. Poor CI users did use assistive listening devices significantly more often than NH listeners wore headphones ($p = .041$), indicating that, although the use of listening technology, in general, may be low among older people, poor CI users, at times, feel the need to seek out assistive technology to improve their hearing outcomes.

Correlations Between Survey Responses and Speech Perception

To further assess our hypothesis that an association may exist between hearing outcomes in CI users and social engagement, correlations were calculated between average

Figure 7. Individual response data for normal-hearing (NH) listeners, good cochlear implant (CI) users, and poor CI users in response to the prompt, "Choose the option that best describes what you are listening to RIGHT NOW."

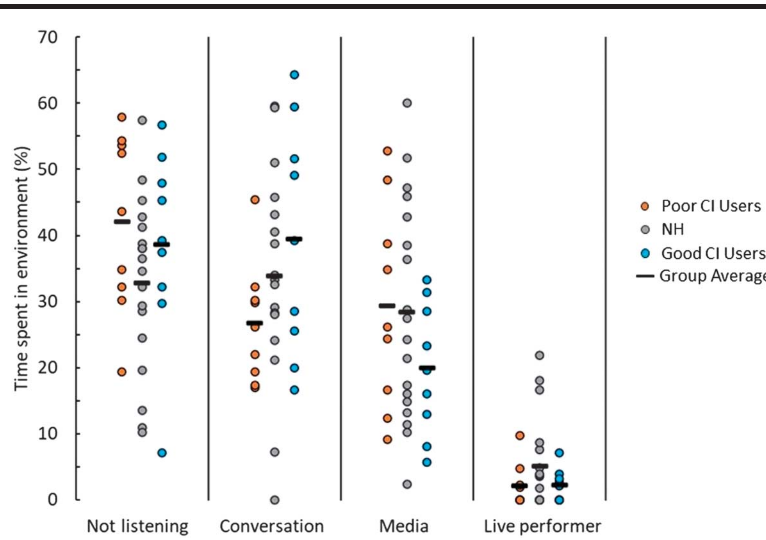
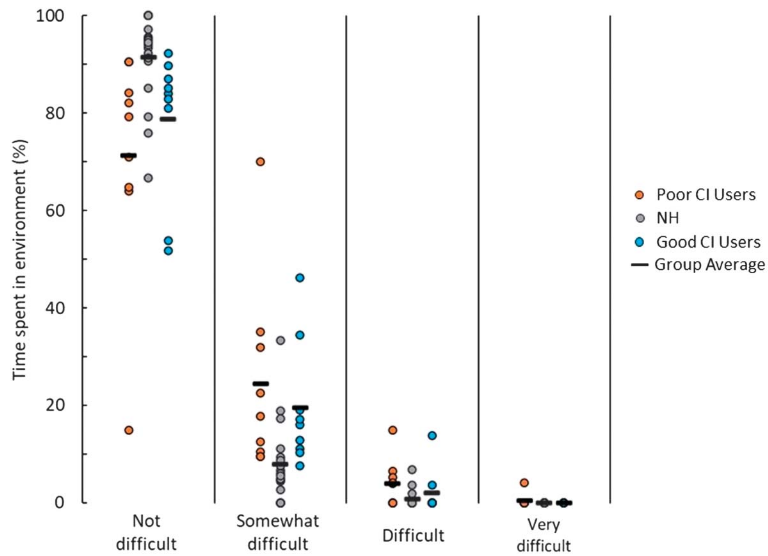


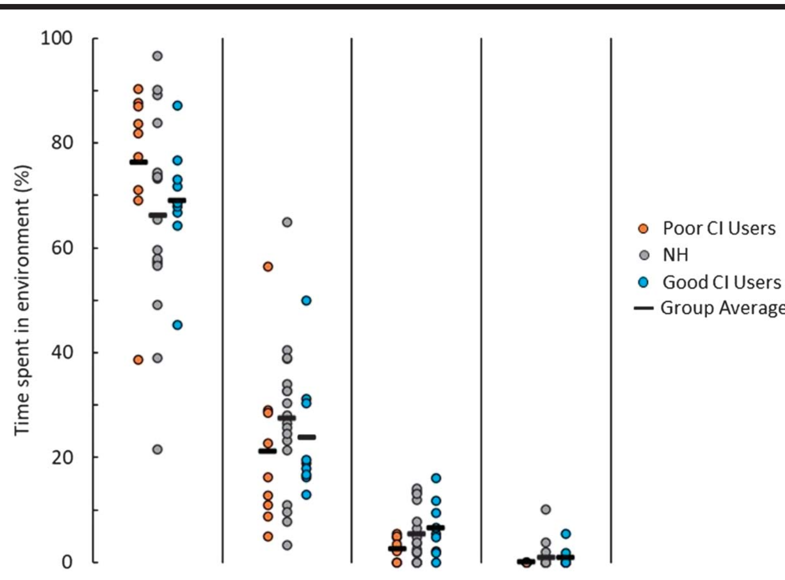
Figure 8. Individual response data for normal-hearing (NH) listeners, good cochlear implant (CI) users, and poor CI users in response to the question, "How difficult is it for you to hear what you are listening to RIGHT NOW?"



speech understanding (from Experiment 1) and a subset of responses from the in-the-moment survey. The *r* and *p* values from these correlations are shown in Table 3.

There was a significant correlation between speech understanding and time spent at home, with better CI users spending less time at home and poorer users spending more time at home ($r = -.54$, $p = .02$). There was not a significant correlation between speech understanding and time spent at work ($r = .09$, $p = .72$), but as many of the CI users were retired, this association was hard to assess in this sample. The amount of time CI users spent conversing with others was also correlated with speech understanding, with better performers spending more time in conversation than poorer performers ($r = .49$, $p = .039$). Though not significant, there was also a trend for better CI users to spend more time interacting with multiple people than poorer CI users ($r = .46$, $p = .054$). The perceived difficulty of understanding speech in daily environments was not significantly correlated

Figure 9. Individual response data for normal-hearing (NH) listeners, good cochlear implant (CI) users, and poor CI users in response to the question, "How much background sound is in your environment RIGHT NOW?"



with speech understanding in CI users (see Table 3, Q4). This is not entirely surprising given the vast range of speech understanding scores associated with individual difficulty ratings, found in Experiment 1. There was not a significant correlation between the level of background sound in daily environments frequented by CI users and speech understanding, indicating that all CI users are in environments with similar levels of noise (see Table 3, Q5). Finally, the use of assistive listening technology (i.e., Mini Mic, Roger Pen, and audio cables) was significantly correlated with speech understanding, with poorer CI users utilizing additional assistive listening technology more often than better CI users ($r = -.51$, $p = .03$).

Reflective Survey Responses

Both the CI group and the NH group completed three out of four (75%, $SD = 0.7$ and 0.8) reflective surveys, on average. Survey responses were normalized for each individual participant (relative to the number of surveys completed) before being included in further analysis. Since the reflective survey was exploratory in nature and more than 20 questions were included for both CI and NH participants, only a subset of the most interesting and informative questions and responses are included in this section.

Questions from the reflective survey probing listening behavior and coping strategies are shown in Figures 10–14. The size of each dot represents the proportion of participants in each group corresponding to a given response. The smallest dot shows responses selected by less than 15% of the group, a slightly larger dot denotes responses from 15% to 25% of participants, the next largest dot shows responses from 26% to 50% of participants, and the largest dot represents responses selected by over half of participants within a group.

Figure 10 shows participant responses to the prompt "Today I used the following strategies to help me hear." Participants could choose multiple response options for this question. As expected, NH listeners most often selected the option "none of the above," indicating that listening strategies are not required on a daily basis for individuals with normal hearing. In contrast, both groups of CI users reported having to employ a listening strategy significantly more often, with good CI users *not* using some sort of coping strategy 17% of the time ($p < .001$) and poor CI users just 8% of the time ($p < .001$). The coping strategy used most often by both good and poor CI users was watching mouth movements and/or facial expressions (visual cues), followed by moving closer to whoever was speaking. Both good and poor CI users used visual facial cues significantly more than NH listeners, reporting watching mouth movements and/or facial expressions 92% ($p < .001$) and 79% ($p < .001$) of the time, compared to 4% of the time by NH listeners. Poor CI users moved closer to whoever was speaking significantly more often than NH listeners ($p = .003$) as well, indicating this behavior was necessary 65% of the time. Not surprisingly, poor CI users also employed multiple coping strategies on a daily basis and used those strategies more often than either good CI users or NH listeners, including moving objects or furniture, adjusting the lighting, or selectively talking to people with louder or clearer voices.

The use of specific listening and social strategies was addressed more directly in a subsequent survey question where participants had to select the strategy they used most often when they could not hear what was being said (see Figure 11). As expected, NH listeners most often reported hearing everything that was spoken to them (the day the survey was completed) and almost always asked someone to repeat themselves if they failed to hear what was said. In contrast, both groups of CI users reported hearing everything spoken to them significantly less often, with good CI users selecting this response 8% of the time ($p = .001$) and poor CI users 19% of the time ($p = .006$). Although asking someone to repeat themselves was the most popular strategy (when necessary) for NH listeners, good CI users actually employed this strategy significantly more often ($p = .004$), having to ask for repetition 77% of the time as opposed to 30% of the time. Interestingly, poor CI users did not ask people to repeat themselves significantly more than NH listeners ($p = 1.000$) but, instead, reported focusing on piecing together what was said (30%) or pretending to hear what was said (10%) almost as often. As a result, poor CI users reported mentally trying to piece together what was said significantly more often than NH listeners ($p = .045$). In general, good CI users seemed to almost universally ask people to repeat themselves when they could not hear what was said, whereas poor CI users were much more varied in their coping strategies.

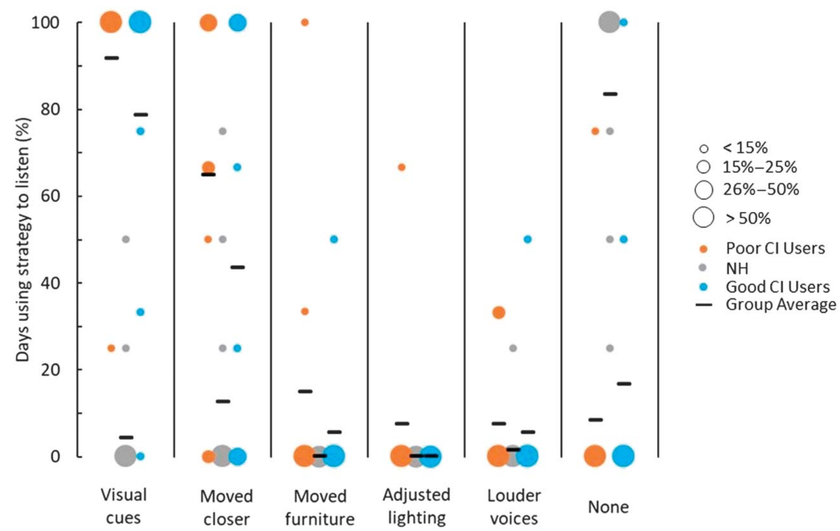
Figures 12 and 13 show responses to questions focusing on especially difficult listening situations. Figure 12 shows responses for why participants decided to put effort into listening, even when it was difficult, and Figure 13 details the types of situations and settings that caused participants to stop putting effort into listening. The response option "other" in Figures 12 and 13 indicates that participants put effort into listening even when it was difficult or stopped putting effort into listening for a reason other

Table 3. Correlations between average speech perception and responses to questions from the in-the-moment survey for cochlear implant users.

Question	*r*	*p*
Q1. Home	−.542	.02*
Q1. Work	.092	.717
Q2. I am alone/doing something independently.	−.323	.191
Q2. I am interacting with multiple people.	.462	.054
Q3. I am not actively listening to anything right now.	−.364	.138
Q3. I am participating in conversation.	.49	.039*
Q4. Not difficult	.352	.152
Q4. Difficult	−.412	.089
Q5. Very little background sound	−.331	.179
Q5. A high level of background sound	.367	.134
Q7. Yes	−.512	.03*

*$p < .05$.

Figure 10. Response data for normal-hearing (NH) listeners, good cochlear implant (CI) users, and poor CI users in response to the prompt, “Today I used the following strategies to help me hear (check all that apply).”



than the options listed in the survey. Perhaps not surprisingly, there were no significant differences between groups regarding what motivated participants to put effort into listening. Overall, all three groups put effort into listening because they felt what was being said was important or they wanted to feel connected to others socially. Good CI users seemed to be more motivated by wanting to feel socially connected than poor CI users or NH listeners, selecting this response 69% of the time, as opposed to 45% of the time, but these differences were not significant (p = .663, p = .477). It is also worth noting that both good and poor CI users reported not putting effort into listening only 7% and 18% of the time, respectively.

This determination is reflected in responses shown in Figure 13 where participants reflected on why they decided to abandon listening, in a given situation. All three groups most often reported that they never stopped trying to listen to something (the day the survey was completed), with good and poor CI users selecting this response 69% and 61% of the time, respectively. Once again, poor CI users reported more reasons for abandoning listening and doing so more often than good CI users. Poor CI users gave background sound and talkers with accents as reasons they, at times, stopped putting effort into listening significantly more often than NH listeners (p = .015, p = .017). The most common reason both good and poor CI users stopped listening was

Figure 11. Response data for normal-hearing (NH) listeners, good cochlear implant (CI) users, and poor CI users in response to the prompt, “Today when I couldn’t hear what was being said, I MOST OFTEN responded by.”

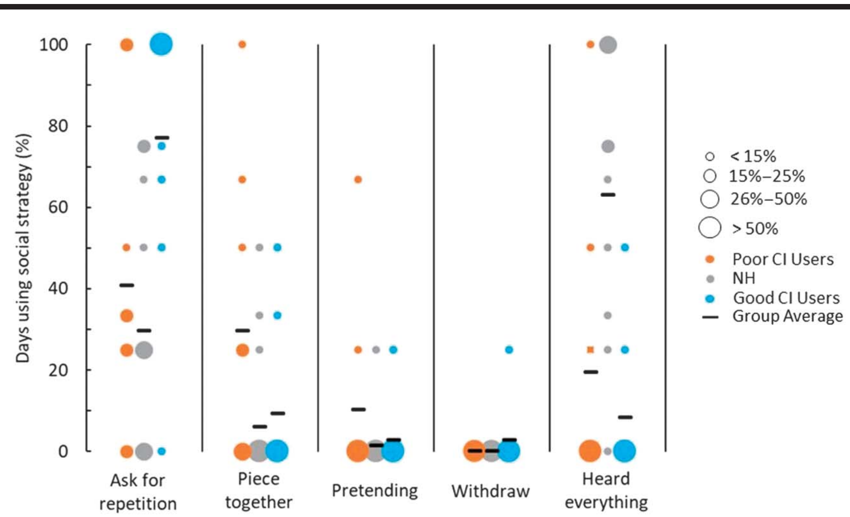
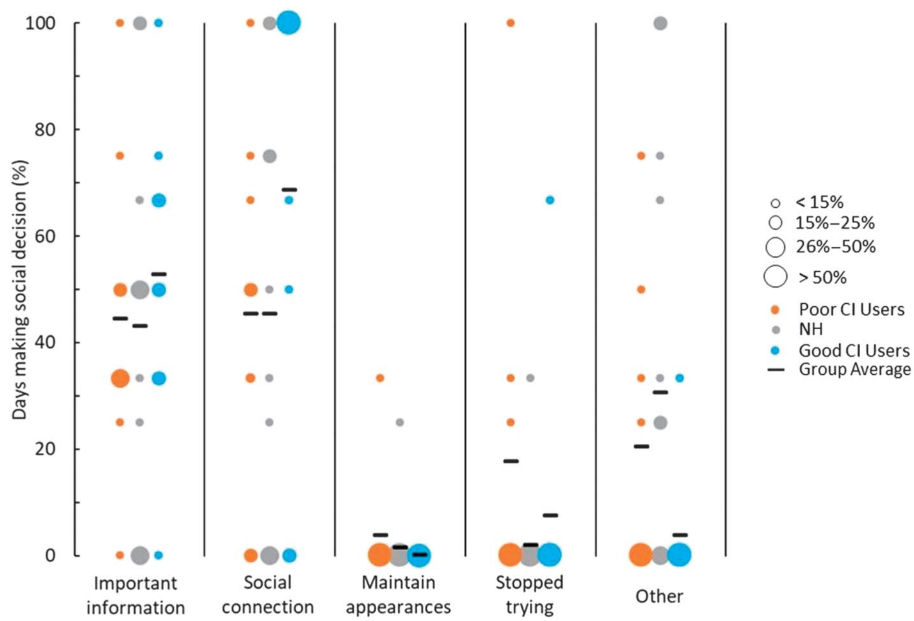


Figure 12. Response data for normal-hearing (NH) listeners, good cochlear implant (CI) users, and poor CI users in response to the prompt, "Today I put effort into listening, even when it was difficult, because (check all that apply)."



the person they were conversing with was speaking too softly, selecting this response 12% and 24% of the time, respectively.

Responses from three questions from the reflective survey probing how much CI users were frustrated by mishearing or not hearing speech in different social settings are shown in Figure 14. In general, the frustration felt from mishearing or not hearing information varies widely across individual participants and is not modulated by actual speech perception abilities. No significant difference was found between good and poor CI users in how bothered they were by their hearing loss across social settings (all *p*s > .15). The type of social interaction (i.e., strangers vs. group setting vs. family) also did not influence how much mishearing or not hearing speech bothered participants (all *p*s > .7). Overall, CI users more often reported

Figure 13. Response data for normal-hearing (NH) listeners, good cochlear implant (CI) users, and poor CI users in response to the prompt, "Today I stopped trying to listen to something because (check all that apply)."

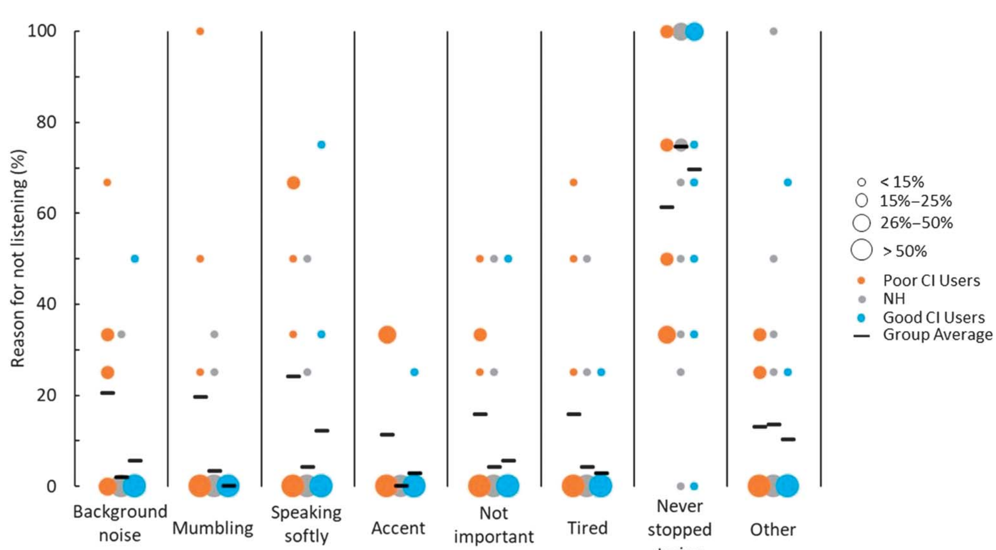
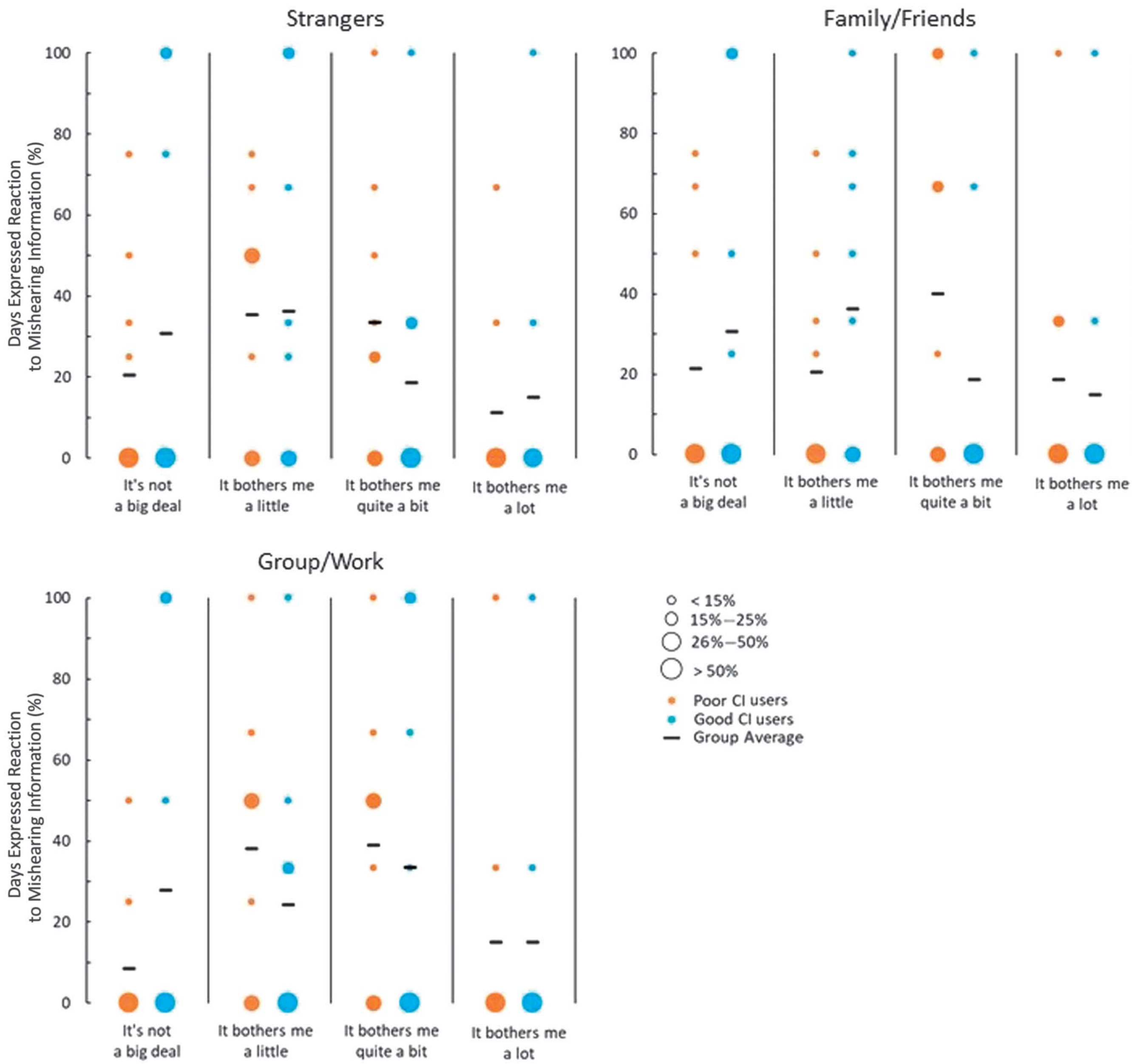


Figure 14. Response data for good and poor cochlear implant (CI) users in response to three versions of the same question: "How much does mishearing or not hearing information bother you (1) when interacting with strangers, (2) when talking in a group setting or at work, or (3) in casual conversation with friends or family?"



being a little bothered or bothered quite a bit when not being able to hear in social situations, as opposed to not at all bothered or bothered a lot.

Discussion

The aim of this study was to explore social engagement and real-world listening behavior in adult CI users and age-matched NH listeners and assess to what extent, if any, speech perception abilities relate to social decisions made in everyday life. We used measures of speech understanding, subjective ratings of listening difficulty, and EMAs administered via a smartphone app to assess social engagement and listening behavior. The main findings and their implications are discussed below.

Perception of Listening Difficulty and Real-World Implications

Understanding the extent to which CI users struggle to understand speech and navigate social situations in everyday life is crucial to assessing the efficacy of CIs in positively influencing quality of life. When deciding whether or not to engage with others socially or allocate effort to listening, a CI user's perception of listening difficulty in a given situation will influence social behavior (Pichora-Fuller, 2016; Pichora-Fuller et al., 2016). One surprising finding of this study was how often CI users indicated that understanding speech in their daily lives was "not difficult" or only "somewhat difficult." Even poorer performing CI users reported speech understanding in their daily lives as "not difficult" 71% of the time and "difficult" or "very difficult" less than 5% of the time. One explanation for this apparent lack of difficulty navigating conversation in daily life is the differences in difficulty perception between individual CI users as well as between NH listeners and CI users, as a group (see Figure 1). In general, CI users rate a much lower level of speech understanding as less difficult than their NH peers. For example, a "not difficult" rating for a CI user in daily life might correspond to understanding 80% of speech, whereas the same rating for an NH participant might indicate 100% speech understanding. This "underrating" of difficulty and large individual differences in rating of difficulty in the CI group could be due, in part, to the difficulty inherent to CI listening, which may be redefined over time and mediated by factors such as performance expectations and duration of hearing loss, which vary across users. Despite these individual differences, based on results from Experiment 1, most CI users will assign a rating of "difficult" or "very difficult" when perceiving 50% of speech or less. This would seem to indicate that over 95% of the time, CI users frequent social environments where they can understand at least 50% of what is being said. Since many of the poor CI users could not achieve 50% speech understanding on PRESTO sentences, even in quiet, this seems to suggest that CI users are relying heavily on visual or other nonauditory cues and the familiarity of speakers to understand speech in daily life.

Responses to questions from the reflective survey seem to support this assertion, where CI users indicated watching mouth movements and facial expressions in more than 75% of daily social situations (see Figure 10). When asked to describe the most difficult and least difficult listening situations encountered during survey days, CI users consistently mentioned the presence of visual information (face-to-face and one-on-one conversation) as promoting ease of listening and the lack of visual information (speaker was turned away, tracking speaker in a group setting) as making listening much more difficult. Familiarity with both the environment (home setting) and the talker (family member or friend) was also a recurring theme reported by CI users as facilitating hearing success. For example, one participant described the least difficult listening situation encountered one day as "talking face-to-face with [my] son, no background noise, in [the] kitchen." Another participant reported an easy listening situation as when she "was sitting across from one person talking directly to that person and that person looking at me while speaking directly to me." Conversely, unfamiliar spaces, unfamiliar talkers, and multiple talkers or background noise were reported as making listening more difficult. One participant described understanding important information given by medical personnel at a local blood drive as especially difficult: "Giving blood today was difficult as they were playing loud music in the background in order to protect our privacy during questioning. The nurse was also very soft spoken and kept forgetting to look at me while speaking." Another CI user related her struggles and frustrations while trying to take part in a workout class at the gym: "[On the] tread mill, meeting [the] gal next to me in class. [I] wanted to know what she said about herself. Also [the] trainer was indicating time and resistance and I strained to see her around [my] screen!" Although the apparent lack of listening difficulty in everyday life among CI users is a positive finding, this result may be a reflection of CI users underrating difficulty in understanding speech when compared to NH listeners, reliance on visual information, and spending most of their time in quiet, familiar environments with familiar talkers.

Speech Understanding Is Related to Time Spent at Home, Time Spent in Conversation, and Use of Assistive Technology in CI Users

Our hypothesis that poorer performing CI users would be less socially engaged than better performing CI users was supported by our data, overall. Speech perception abilities of CI users were significantly correlated with the amount of time spent at home, with better CI users spending less time at home and poorer CI users spending more time at home. Speech understanding was also positively correlated with the amount of time spent conversing with others, with poor CI users spending less time in conversation than good CI users. Across multiple questions, poor CI users reported more difficulty in everyday environments and were less socially active than their NH peers. Poor CI users also used assistive listening technology (i.e., Mini Mic, Roger Pen, etc.) more often than NH listeners used earbuds, although assistive device usage was very low overall. Although this is not a direct comparison, it does indicate more use of hearing technology, in general, among poor CI users than NH peers might seek out, by choice. It is also worth noting that, despite the time and energy that has gone into creating assistive listening technology, even the poor CI users were only using it 8% of the time, on average. Nontechnological strategies, such as using visual cues, moving closer to a speaker, moving objects or furniture, asking someone to repeat themselves, or piecing together what was said, seem to be more common coping strategies among both good and poor CI users.

In contrast to the differences between poor CI users and their NH peers, there were no significant differences in responses to questions probing social engagement between good CI users and NH participants. This is very encouraging, as it seems to indicate that, for some individuals, CIs enable the same level of social engagement as found in people with NH. However, this conclusion should be interpreted with caution. First, the average age of participants in this study was 62 years old, and as a result, many participants were retired and less socially active overall than a younger demographic might be. Second, there are still significant differences in *how* good CI users and NH participants successfully navigated social situations. Although NH listeners usually heard everything spoken to them and thus rarely used any listening coping strategies, good CI users relied on visual cues, asking for repetition and moving closer to the speaker to facilitate social interactions.

Speech Understanding Not Related to Time Spent at Work, Time Spent in Noisy Environments, or CI Usage

An unexpected finding from the EMA data was that CI users (good or poor) did not spend less time in noisy environments than their NH peers, and time spent in environments with high or low levels of background noise did not correlate with speech understanding in CI users. This is surprising, given that a frequent complaint of CI users is difficulty in understanding speech in background noise. However, it is important to note that CI users spent over 70% of their time in environments with very little background sound. NH listeners also spent most of their time in quiet environments (over 65%), but it would be interesting to see how these results might differ in younger adults or children who might spend more time in noisy environments, such as bars or gymnasiums.

There was also no difference in the amount of time spent at work between NH participants and CI users, and speech understanding was not correlated with time spent working for CI users. However, since many participants were retired and the overall sample size was fairly small, the conclusions that can be drawn in terms of how hearing loss may impact employment are limited. Since hearing loss and other disabilities are often associated with lower levels of employment and socioeconomic status (Emmett & Francis, 2015; He et al., 2018), this would be a relevant factor to explore in a younger population of CI users and NH individuals.

The amount of time CI users spend wearing their devices in everyday life and its influence on CI outcomes is still not fully understood. Clinicians often counsel patients on the importance of wearing their CIs as much as possible, especially in the weeks and months immediately following implantation. A recent study by Holder et al. (2020) found a correlation between daily CI use and speech perception outcomes, but since the participants were experienced CI users, it is hard to know if more CI usage facilitates better hearing outcomes or if poor hearing outcomes lead to less usage of the device. Interestingly, in this study, there were no significant differences in device usage between good and poor CI users. This seems to indicate that CI users are not achieving poorer speech understanding outcomes simply because they are not wearing their CIs as much or as often as better users. Bilateral CI users wore both CIs more than 70% of the time, and unilateral users wore their CI more than 90% of the time. It is interesting to note that both unilateral and bilateral users wore no CI processors about 10% of the time. This may indicate a need for listening breaks on the part of both good and poor CI users.

Individual Differences in Level of Frustration Felt Due to Hearing Loss in Everyday Life

Mishearing or not hearing information in conversation is a daily reality of CI users. Despite this social barrier, the level of frustration felt by individual CI users when this occurred was not modulated by speech understanding. There was a huge amount of variability in responses across users when asked how much mishearing or not hearing information bothered them (see Figure 14) that does not seem to be related to overall hearing outcomes or social setting. Some star performers are not bothered at all by missing spoken information, some poor performers are very bothered, and vice versa. Likewise, some CI users seem to be bothered more by not hearing information when speaking with friends and family, whereas others are more affected by difficulties encountered when talking to strangers. It may be that frustration felt by CI users is more closely related to differences in personality or expectations, but this cannot be confirmed from our data, as these dimensions were not assessed. However, the lack of correlation between hearing outcomes and frustration in daily life is important for clinicians to understand when counseling patients.

Conclusions

Social engagement, listening behaviors, and perception of listening difficulty were measured in 18 adult CI users and 18 age-matched NH listeners and related to speech perception abilities. The main findings can be summarized as follows:

- The perception of listening difficulty differs greatly between CI users and NH listeners, with CI users consistently rating poorer levels of speech understanding as less difficult than their NH peers.
- CI users spend most of their time in listening and social situations they find to be “not difficult.” The use of visual cues, such as lipreading, and social engagement with familiar people in familiar settings may facilitate this ease of listening in daily life.
- Lower performing CI users spend more time at home and less time in conversation than higher performing CI users or age-matched NH listeners. Thus, there is an association between hearing outcomes and social engagement in CI users.
- Good CI users did not spend more time in noisy environments and also did not wear their CIs more often in daily life than poor CI users. In general, CI users in this study wore their devices the vast majority of the time and also spent lots of time in quiet environments.
- The frustration experienced by individual CI users as a result of their hearing loss is not mediated by speech perception abilities or differences in social settings. It is important for clinicians to understand that other factors may be mediating frustration and to counsel patients according to their individual goals.

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