Published in final edited form as:

Ear Hear. 2017 ; 38(2): 236–243. doi:10.1097/AUD.0000000000000379.

Visual Temporal Acuity is Related to Auditory Speech Perception Abilities in Cochlear Implant Users

Kelly N. Jahn¹, Ryan A. Stevenson^{2,3}, and Mark T. Wallace¹

¹Department of Hearing and Speech Sciences, Vanderbilt University, Nashville, Tennessee, USA

²Department of Psychology, University of Western Ontario, London, Ontario, Canada

³Brain and Mind Institute, University of Western Ontario, London, Ontario, Canada

Abstract

Objective—Despite significant improvements in speech perception abilities following cochlear implantation, many pre-lingually deafened cochlear implant (CI) recipients continue to rely heavily on visual information to develop speech and language. Increased reliance on visual cues for understanding spoken language could lead to the development of unique audiovisual integration and visual-only processing abilities in these individuals. Brain imaging studies have demonstrated that good CI performers, as indexed by auditory-only speech perception abilities, have different patterns of visual cortex activation in response to visual and auditory stimuli as compared to poor CI performers. However, no studies have examined whether speech perception performance is related to any type of visual processing abilities following cochlear implantation. The purpose of the present study was to provide a preliminary examination of the relationship between clinical, auditory-only speech perception tests and visual temporal acuity in pre-lingually deafened adult CI users. It was hypothesized that pre-lingually deafened CI users who exhibit better (i.e., more acute) visual temporal processing abilities would demonstrate better auditory-only speech perception performance than those with poorer visual temporal acuity.

Design—Ten pre-lingually deafened adult CI users were recruited for this study. Participants completed a visual temporal order judgment (vTOJ) task to quantify visual temporal acuity. To assess auditory-only speech perception abilities, participants completed the consonant-nucleus-consonant (CNC) word recognition test and the AzBio sentence recognition test. Results were analyzed using two-tailed partial Pearson correlations, Spearman's rho correlations, and independent samples t-tests.

Results—Visual temporal acuity was significantly correlated with auditory-only word and sentence recognition abilities. Additionally, proficient CI users, as assessed via auditory-only speech perception performance, demonstrated significantly better visual temporal acuity than non-proficient CI users.

Address correspondence to Kelly N. Jahn (current address): Department of Speech and Hearing Sciences, University of Washington, 4131 15th Ave NE, Seattle, WA 98105, USA. kelly.n.jahn@gmail.com.

Conflicts of Interest

No conflicts of interest were declared for any author.

Conclusions—These findings provide the first behavioral evidence that visual temporal acuity is related to post-implantation CI proficiency as indexed by auditory-only speech perception performance. These preliminary data bring to light the possible future role of visual temporal acuity in predicting CI outcomes prior to implantation, as well as the possible utility of visual training methods in improving CI outcomes.

Introduction

Many pre-lingually deafened individuals with severe-to-profound sensorineural hearing loss benefit from cochlear implantation. However, these individuals still often exhibit deficits in receptive and expressive communication skills compared to their normal-hearing peers (Rinaldi et al. 2013; Caselli et al. 2012). One likely reason for these deficits is that individuals who receive a cochlear implant (CI) at an early age utilize a modified auditory signal to develop spoken language skills, given that CIs rely on a limited number of independent channels to stimulate groups of surviving auditory neurons. Thus, pre-lingually deafened individuals must rely more heavily on information from other sensory modalities such as vision to develop expressive and receptive language (Lachs et al. 2001; Kirk et al. 2007). Increased reliance on visual cues and lip reading for understanding spoken language likely results in the development of audiovisual integration and visual-only processing abilities that are different from individuals with normal hearing.

In fact, both human and animal studies suggest that a deficit in one sensory modality, such as audition, can induce compensatory mechanisms leading to increased abilities in spared sensory modalities, such as vision (Strelnikov et al. 2013). Evidence of cross-modal perceptual compensation has been observed in animal models with both congenital and adult-onset deafness (Allman et al. 2009; Lomber et al. 2010; Barone et al. 2013). In humans, neuroimaging and electrophysiology data show that the visual cortex in deaf individuals can be activated by speech-related auditory inputs, suggesting that these individuals integrate and/or process auditory information and visual speech cues differently than do normal-hearing individuals. Reinforcing this view, functional neuroimaging data has demonstrated that the visual cortex of adult CI recipients is more active than that of normal-hearing individuals when listening to meaningful speech sounds, and this activation increases with CI experience (Giraud et al. 2001a; Giraud et al. 2001b). Evidence for enhanced activation of visual cortex while listening to meaningful auditory speech sounds suggests that there may be a relationship between speech perception abilities and the amount of visual cortical activation in individuals with CIs, and likewise, a link between visual perceptual abilities and auditory/audiovisual speech perception in CI users.

The importance of atypical visual cortical activation has been observed via electroencephalography (EEG) studies where CI users were divided based on auditory speech perception abilities into ‘poor performers’ and ‘good performers’ (Doucet et al. 2006; Buckley and Tobey 2011; Kim et al. 2016). These studies showed that good auditory speech perception abilities are related to larger visual evoked potentials in the visual cortex in response to visual stimuli. On the other hand, poor auditory speech perception abilities are related to enhanced visual-evoked brain activity in more anterior and temporal regions of the cortex (Doucet et al. 2006; Buckley and Tobey 2011; Kim et al. 2016). This relationship has

been demonstrated in both pre-lingually deafened (Doucet et al. 2006; Buckley and Tobey 2011) and post-lingually deafened (Kim et al. 2016) adult CI users. Thus, cross-modal plasticity may account for some of the variability observed in speech perception performance after cochlear implantation and good CI performers may utilize visual cues differently than poor CI performers to compensate for the degraded auditory signal.

These findings suggest an important role for vision in CI outcomes; a suggestion that seems obvious in light of the important role that vision plays in speech processing and perception. Indeed, prior research has demonstrated the powerful influence of vision on auditory processing in individuals with normal hearing as well as those with hearing loss. The ability to observe visual articulations in addition to hearing the speaker during a linguistic utterance significantly improves a listener's speech perception performance in both quiet and in noise (Sumby & Pollack 1954; Erber 1975; MacLeod & Summerfield 1987; Grant & Seitz 2000; Bernstein et al. 2004; Tye-Murray et al. 2007a). Similar audiovisual benefit for speech perception performance has also been shown in individuals with CIs (Kaiser et al. 2003; Rouger et al. 2007; Kirk et al. 2007). Despite the acknowledged role of vision in shaping speech perceptual abilities, the current gold standard for the clinical quantification of CI benefit is the assessment of speech perception skills administered in an auditory-only format (Hay-McCutcheon et al. 2009). Thus, it seems evident that in addition to assessing changes in speech perception, changes in visual and audiovisual processing should be considered in the clinical assessment of CI speech perception benefit.

Few studies have empirically characterized visual function in CI users, or examined whether an individual's visual processing abilities change following intervention with CIs. This is despite the fact that CI users rely to a great extent on visual inputs and lip reading for understanding speech. For example, post-lingually deafened CI recipients maintain greater speech reading abilities and higher visual identification levels than do normal-hearing individuals, even several years following cochlear-implantation (Rouger et al. 2007; Moody-Antonio et al. 2005). It has also been shown that CI users rely more heavily on the visual channel in the perception of the McGurk effect (in which the pairing of incongruent auditory and visual signals results in a novel percept) than do normal-hearing individuals (Rouger et al. 2008). For example, during the McGurk effect, CI users tend to perceive the syllable represented by the facial movements of the speaker rather than the auditory percept, whereas normal-hearing individuals equally utilize both the visual and auditory cues when making a perceptual decision (Desai et al. 2008; Huyse et al. 2013; Rouger et al. 2008; Schorr et al. 2005; Tremblay et al. 2010). Based on these findings, it is possible that CI recipients with better visual perception abilities may become more proficient CI users than individuals with poorer visual perception abilities. However, no studies have examined whether speech perception performance is related to any type of visual processing abilities following cochlear implantation.

One aspect of visual function that is likely to be important in processes such as speech perception is temporal acuity. Visual temporal acuity plays an important role in processing the dynamic properties of the visual world, such as motion, and likely works in concert with auditory temporal processes for evaluation of naturalistic and dynamic audiovisual signals such as speech. Indeed, audiovisual temporal acuity represents a critical construct for the

rapid and accurate “binding” of auditory and visual speech elements (i.e., phonemes and visemes) into a single perceptual entity (Andersen et al. 1976; Shams et al. 2000; Stevenson et al. 2012). Thus, as auditory and visual stimuli are presented in close temporal proximity, their likelihood of being perceptually bound increases; conversely, when the temporal interval between two stimuli increases, the likelihood of multisensory integration and binding decreases (Conrey & Pisoni 2006; Hirsh & Fraisse 1964; Keetels & Vroomen 2005; Miller & D’Esposito 2005; Powers et al. 2009; Spence et al. 2003; Stevenson et al. 2010; van Atteveldt et al. 2007; van Wassenhove et al. 2007; Vatakis & Spence 2006).

Collectively, this temporal interval is captured within the probabilistic construct known as the temporal binding window (TBW; Colonius & Diederich 2004; Foss-Feig et al. 2010; Hairston et al. 2005; Powers et al. 2009; Stevenson & Wallace 2013; Wallace & Stevenson 2014). It has been demonstrated that the TBW is highly variable across individuals, leading to varying degrees of audiovisual integration abilities. Individuals with narrower TBWs are better able to dissociate asynchronous audiovisual inputs when auditory stimuli lag visual stimuli (Grant et al. 2004; Stevenson et al. 2010; Stevenson et al. 2012; Stevenson & Wallace 2013). This is beneficial when interacting with one’s environment, as auditory and visual signals have significantly different energy propagation rates and neural transduction and conduction times (Corey & Hudspeth 1979; King & Palmer 1985; Lamb & Pugh 1992; Lennie 1981; Grant et al. 2004). The arrival time of an auditory stimulus is therefore delayed compared to the visual component of the stimulus. Thus, visual temporal processing abilities are likely important for appropriate integration of audiovisual speech information, and the relationship between visual temporal processing abilities and speech perception abilities in CI users should be better characterized.

The present study aimed to examine the relationship between the auditory-only speech perception tests used in clinical settings to evaluate CI proficiency and visual temporal acuity measured using a visual temporal order judgment (vTOJ) task. Unisensory behavioral tasks were utilized to maintain clinical relevance and consistency with prior research studies. Thus, as auditory-only testing is currently the gold standard for assessing CI candidacy and outcomes in clinical settings, participants completed auditory-only word and sentence recognition tasks. Second, participants completed a visual-only task chosen due to the electrophysiological and neuroimaging findings suggesting that enhanced activation of visual cortex in response to visual stimuli is associated with better auditory-only speech perception outcomes in CI users (Doucet et al. 2006; Buckley & Tobey 2011; Kim et al. 2016). It was hypothesized that pre-lingually deafened CI users who exhibit better (i.e., more acute) visual temporal processing abilities would demonstrate better post-implantation auditory-only speech perception scores than those with poorer visual temporal acuity. Furthermore, it was predicted that proficient CI users would demonstrate significantly better visual temporal acuity than non-proficient CI users. These data represent one of the first attempts to relate psychophysically characterized visual temporal function to post-implantation clinical audiological measures of CI outcomes in individuals with pre-lingual deafness.

Methods

Participants

Participants included 10 adults with pre-lingual bilateral severe-to-profound sensorineural hearing loss who used at least one CI (age 18–43 years, mean = 28.4 years). Four of the participants were bilateral CI users, four used a CI in one ear and a hearing aid in the contralateral ear (bimodal), and two were unilateral CI users who did not use an amplification device on the ear contralateral to the implanted ear. The unaided hearing thresholds of the non-implanted ears for the bimodal and unilateral CI users are depicted in Figure 1. The mean age at the time of the first intervention for hearing loss (i.e., appropriately-fit amplification or cochlear implantation) was 2.3 years (SD = 1.2 years; range = 0.7 – 5 years). The mean hearing age, based on the age at first intervention, was 26.1 years (SD = 9.4 years; range = 15.7 – 41.7 years). The mean age at the time of cochlear-implantation was 21.6 years (SD = 15.2 years; range = 1.2 – 42.1 years), with a mean duration of CI experience at the time of the study of 6.8 years (SD = 9.0 years; range = 0.6 – 22.1 years). Three participants received a CI prior to four years of age, a crucial period for language acquisition (Yucel & Derim 2008).

Each of the participants received audiological services at the Vanderbilt Bill Wilkerson Center (VBWC) in Nashville, Tennessee. All subjects were screened for normal or corrected-to-normal vision using a standard Snellen eye chart and had no history of neurological disorders or developmental delay. Each participant primarily used spoken language to communicate and was a native English speaker. The Vanderbilt University Institutional Review Board (IRB) approved the procedures for this study.

Procedures

I. Assessment of Visual Temporal Acuity—Participants completed a visual temporal order judgment (vTOJ) task in the Multisensory Research Laboratory at Vanderbilt University (Stevenson et al 2013; Stevenson et al. 2014). All vTOJ testing was conducted in an unlit sound attenuating WhisperRoom™ (Model SE 2000; Whisper Room Inc, Morristown, TN). Visual stimuli were presented on a 16 × 13 inch computer screen, with a refresh rate of 100 Hz, and with a black background. All stimuli were programmed and randomized using MatLab software (MATHWORKS Inc., Natick, MA) with the Psychophysics Toolbox extensions (Brainard 1997; Pelli 1997).

During this computer-based task, participants were presented with two white circles 1.5 cm in diameter on a black screen. For each trial, one circle flashed 2.5 cm above the fixation cross (1 cm × 1 cm) and the other circle flashed 2.5 cm below the fixation cross. The subject was asked to report whether the top or the bottom circle flashed first for each trial by selecting either the number “1” or “2” on a standard computer keyboard. The participant selected the number “1” to indicate that the top circle flashed first and the number “2” to indicate that the bottom circle flashed first. Eight different stimulus onset asynchronies (SOAs) were used, representing the amount of time, in milliseconds (ms), separating the visual presentation of the top versus the bottom circle on each trial. The SOAs were 10 ms, 20 ms, 30 ms, 40 ms, 60 ms, 80 ms, 100 ms, and 150 ms. These SOAs were chosen based on

previous work suggesting that the performance-intensity function of the vTOJ task is steepest below SOAs of 40 ms and that wider SOA gaps are acceptable after the SOA performance reaches asymptote (>80 ms) (Stevenson et al. 2014; Stevenson et al. 2013). SOA presentation was randomized using MatLab programming. The top and bottom circles flashed first in an equal, randomized, number of trials. Twenty trials were completed at each SOA, and responses were scored as either correct or incorrect.

II. Assessment of Auditory Speech Perception—Speech perception data was collected from each participant, and was gathered either during the patients' most recent audiology clinic visit at the Vanderbilt Bill Wilkerson Center, or collected by the experimenters on the same day as the vTOJ testing. All clinical speech perception data was collected within one year of the vTOJ test date and represented asymptotic performance for the individual. The speech perception tests were administered and scored by the patient's licensed clinical audiologist or a supervised audiology doctoral student.

Each participant completed one 50-word list from the Consonant-Nucleus-Consonant (CNC) monosyllabic word test (Peterson and Lehiste 1962) and one 20-sentence list from the AzBio Sentence Lists (AzBio; Spahr et al. 2012). For each test, participants verbally stated their response. All speech stimuli were presented from zero degrees azimuth in the soundfield at a calibrated level of 60 dB SPL.

Auditory-only speech perception testing was completed with all amplification devices activated, representing the best-aided condition, and using each individual's preferred everyday device settings. A licensed audiologist saw each patient for a CI programming appointment prior to speech perception testing, assuring that the devices were functioning appropriately at the time the speech data was collected.

III. Statistical Analyses—Statistical analyses comparing vTOJ performance to the clinical speech perception data were conducted using Graphpad Prism statistics software. Two-tailed Pearson correlations were used to examine the relationships between visual threshold and auditory-only speech perception. Independent samples t-tests were employed to compare the visual thresholds of proficient versus non-proficient CI users. An α -level of 0.05 was used for all statistical analyses.

Additionally, Spearman rank-order correlations were conducted to assess any possible relationship between demographic variables and experimental measures. No correlations proved significant; however, given the small sample size, all r_s and p-values are reported in Table 2.

Results

Visual Temporal Acuity

Performance on the vTOJ task for each individual was assessed as the proportion of correct responses at each SOA. This refers to the proportion of trials during which the subject correctly identified whether the top or the bottom circle flashed first on the computer screen. Additionally, a visual threshold was calculated for each participant using the glimfit function

in MatLab. The visual threshold represents the SOA at which the individual would achieve 75% correct on the vTOJ task. A lower visual threshold reflects better performance on the vTOJ task, or better visual temporal acuity. Average visual threshold and visual performance across each SOA for the participants is shown in Figure 2. As expected, performance declined as SOA decreased. The mean visual threshold across participants was 28.4 ms, with individual performances reported in Table 1.

Auditory Speech Perception

Accuracy was measured for both the CNC monosyllabic word lists (Peterson & Lehiste 1962) and the AzBio Sentence Lists (Spahr et al. 2012). For CNC lists, each word was scored as either correct or incorrect, yielding a percent correct score for each test. For AzBio sentence lists, each word within the sentence was scored as either correct or incorrect. The mean CNC word recognition score was 63.6% (SD = 27.4; Range = 12-98%) and the mean AzBio sentence recognition score was 73.5% (SD = 27.8; Range = 9-100%). Individual performance on the CNC word recognition task and the AzBio sentence recognition task are reported in Table 1.

Correlations Between vTOJ Performance and Speech Measures

Two-tailed Pearson correlations revealed that CNC word recognition scores were significantly negatively correlated with visual thresholds (Figure 3a; $r_{(10)} = -0.87$, $p = 0.0012$). Similarly, AzBio sentence recognition scores were significantly negatively correlated with visual thresholds (Figure 3b; $r_{(10)} = -0.94$, $p < 0.0001$). Collectively, this pattern of results suggests that pre-lingually deafened adult CI users with lower visual thresholds, which are indicative of better visual temporal acuity, have better auditory-only word and sentence recognition scores.

Proficient versus Non-Proficient Group Comparisons

Finally, the participants were split into two groups based on their word and sentence recognition scores: proficient CI users and non-proficient CI users. Proficiency was determined by comparison to the mean CNC performance of the group. That is, proficient CI users were defined as those who achieved a CNC word recognition score above the group mean CNC score (63.6%) and non-proficient CI users were defined as those who achieved a CNC word recognition score below the group mean. Participants who were characterized as proficient or non-proficient based on CNC word recognition were also proficient or non-proficient, respectively, on AzBio sentence recognition. Dividing the participants into proficient and non-proficient speech perception groups simply provides another way to characterize the relationship between auditory-only speech perception abilities and visual-only temporal acuity.

Figure 4 shows the average visual thresholds of the proficient and non-proficient CI users. As can be seen, proficient CI users demonstrated better visual temporal acuity than non-proficient CI users. Independent-samples t-tests showed that there was a significant difference in the average visual threshold of the proficient ($M = 14.4$, $SD = 10.2$) and non-proficient ($M = 42.4$, $SD = 17.2$) groups ($t(8) = 3.124$, $p = 0.0141$, $d = 1.98$). These findings illustrate that pre-lingually deafened adult CI users who are proficient on auditory-only

speech perception tests have better visual-only temporal acuity when compared with pre-lingually deafened adult CI users who are not proficient on auditory-only speech perception tests.

Discussion and Conclusions

These preliminary data represent the first attempt to relate visual temporal processing abilities to post-implantation clinical measures of CI outcomes in individuals with pre-lingual hearing loss. Results show a strong relationship between visual-only temporal acuity and clinical assessments of auditory-only speech perception. This suggests that pre-lingually deafened adult CI users with good visual-only temporal processing abilities have stronger auditory-only speech perception abilities following cochlear-implantation than those with poor visual temporal acuity.

These preliminary findings provide the first behavioral evidence that low-level visual temporal abilities are related to post-implantation CI proficiency as indexed by auditory-only speech perception measures. Prior neuroimaging evidence complements the results of the present study. Greater activation of the visual cortex occurs in good CI performers as compared to poor CI performers in response to visual stimuli (Doucet et al. 2006; Buckley & Tobey 2011; Kim et al. 2016). Furthermore, poor CI performers demonstrate more anteriorly distributed cortical activation following visual stimulation, whereas good CI performers demonstrate more localized cortical activation near the primary visual cortex (V1) (Doucet et al. 2006; Buckley & Tobey 2011; Kim et al. 2016). Notably, greater activation in more anterior cortical regions, such as the auditory cortex, in response to visual stimulation is thought to have detrimental consequences for CI rehabilitation, as moderate CI performers demonstrate more pronounced visual activation of auditory cortex compared to good CI performers (Sandmann et al. 2012). In sum, greater activity in response to visual stimuli is associated with better auditory-only CI performance when the activity is largely restricted to visual cortex. If, on the other hand, an increase in cortical activity occurs in auditory regions, which is indicative of more extensive cortical reorganization, this may lead to decreases in auditory-only CI performance.

The evidence provided by the present study may serve as a behavioral correlate to such imaging studies, as more localized patterns of V1 activation in response to visual stimuli have been shown to be associated with better speech perception abilities in CI users. These findings suggest that pre-lingually deafened adult CI users who perform better on the vTOJ task possibly have more localized patterns of visual cortex activation in response to the task's visual stimuli. Perhaps greater reorganization of the auditory cortex prior to implantation, or incomplete reversal of deafness-induced cross-modal reorganization following implantation, limits the clinical benefit of the CI for poor performers. However, to our knowledge, neural activity in response to the vTOJ task has not been characterized. Further research is necessary to determine whether different patterns of visual cortex activation are in fact associated with performance on the vTOJ task.

As a neural correlate to the vTOJ task has not yet been characterized, it is important to consider alternative explanations for the present findings. First, the vTOJ task used in this

study, although short in duration (7 minutes), requires sustained visual attention. There is a growing body of evidence suggesting that pre-lingually deafened individuals exhibit enhanced peripheral visual attention compared to individuals with normal-hearing (Loke & Song 1991; Bavelier et al. 2000; Nava et al. 2008; Dye & Bavelier 2012). In fact, Nava and colleagues (2008) demonstrated that deaf individuals respond significantly faster during the hardest vTOJ condition than do normal hearing controls when the visual targets are presented to the peripheral visual field. With regards to the central visual field, however, some studies have reported poorer central visual field attention in pre-lingually deafened individuals compared to normal-hearing controls (Quittner et al. 1994; Smith et al. 1998; Proksch & Bavelier 2002; Parasnis et al. 2003; Dye & Bavelier 2012) whereas other studies have reported no difference in central visual attention (Neville & Lawson 1987b; Dye et al. 2009; Dye & Bavelier 2010; Dye & Bavelier 2012). Pre-lingually deafened individuals also exhibit greater impulsivity during tasks involving sustained visual attention (Parasnis et al. 2003; Yucel & Darim 2008; Dye & Bavelier 2012). This impulsivity may be affected by age at cochlear-implantation and duration of deafness, as greater impulsivity during sustained visual attention tasks has been observed in children implanted after four years of age (Yucel & Dari 2008). Furthermore, Kim et al. (2016) suggest that better speech perception outcomes are associated with enhanced central visual field attention in post-lingually deafened adult CI users. Given the variability in demographic factors (i.e. hearing experience; device configuration) for the participants in this study, it is possible that differences in visual attention and impulsivity may account for some of the observed variability in visual temporal performance.

Additionally, it is possible that individuals with better general cognitive ability may perform better on both the auditory-only speech perception and visual-only temporal perception measures. In fact, Park et al. (2015) observed that higher nonverbal IQ is associated with better post-operative auditory speech perception performance in pre-lingually deafened pediatric CI users. Further research is needed to characterize speech perception and visual temporal outcomes as a function of general cognitive ability in CI users.

Limitations

Pre-lingually deafened adult CI users are a relatively small population. As such, the sample size of the present study is relatively small and the results of this study are considered to be preliminary. Further research employing a larger sample size is necessary in order to draw more generalized conclusions regarding the relationship between visual-only temporal perception and auditory-only speech perception in pre-lingually deafened adult CI users. Additionally, while conclusions can be drawn from the present study about the relationship between visual-only temporal acuity and auditory-only speech perception abilities in CI users, given the lack of control group, it is unknown whether this relationship is specific to CI users. It is possible that the association of better auditory speech perception with better visual temporal perception is also present in normal-hearing individuals. However, even if this trend is consistent across different populations, it is still nonetheless an intriguing relationship that may provide insight into factors that are associated with CI proficiency. Third, there was a high degree of variability in the demographic characteristics of the current sample including device configuration, duration of CI experience, and age at implantation.

Future studies with more participants may be able to better control for the variability in hearing experience.

Finally, it is possible that better auditory-only speech perception abilities allow for the development of better visual-only temporal perception, and vice versa. As described above, there may be many other factors such as general cognition, vocabulary, degree of visual attention, hearing experience, and lip-reading abilities, among others, that allow for development of better auditory-only speech perception, better visual-only temporal perception, or both. Further research is warranted to determine the causative nature of the observed relationship.

Implications and Future Directions

The implications of this research in the field of aural rehabilitation and for clinical assessment of CI outcomes are important. Behavioral and neuroimaging evidence suggest that visual-only processing abilities in adult CI patients are significantly correlated with CI outcomes as measured by proficiency on auditory-only speech perception tests. Speech perception testing in an auditory-only format is the current gold standard for the clinical quantification of CI benefit (Hay-McCutcheon et al. 2009). However, the results of this preliminary study show clinical promise that behavioral indices of visual-only performance may also provide insight into CI proficiency for pre-lingually deafened adult patients.

Additionally, it is crucial to continue to develop methods to predict CI outcomes prior to implantation. Data for the present study was collected post-implantation, so pre-implantation visual processing performance is unknown and conclusions cannot be drawn regarding the predictive abilities of the vTOJ measure for future CI outcomes. However, Strelnikov et al. (2013) demonstrated that activity levels in the visual processing areas of the occipital cortex immediately following cochlear implantation are related to proficiency of auditory recovery and speech perception abilities six months post-implantation. Taken together with the present findings, the ability of behavioral indices of pre-implantation visual temporal perception to predict CI outcomes should be explored. Understanding the factors that relate to better performance with a CI can help with CI candidacy evaluations, counseling, and development of realistic expectations of CI benefit.

Acknowledgments

We thank the participants for generously donating their time for this study. We also thank Drs. Rene Gifford and Andrea Hillock-Dunn for valuable discussion, and Iliza Butera for assistance with participant recruitment. Support for this work from MTW came from the NIH CA183492 grant and the Vanderbilt Bill Wilkerson Center. Support for this work from RAS came from a Banting Fellowship granted by the Canadian Natural Sciences and Engineering Research Council (NSERC) and The Autism Research Training Program funded by The Canadian Institutes of Health Research (CIHR). A portion of this work was presented at the AudiologyNow! 2016 convention in Phoenix, AZ in April 2016.

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Figure 1. Average unaided hearing thresholds of the non-implanted ears for the bimodal and unilateral CI participants. Standard error bars are shown.

Figure 2.

Average visual performance across all stimulus onset asynchronies (SOAs) and average visual threshold. A sigmoid function was used to fit the curve and standard error bars are shown.

Figure 3.

For each panel, a lower visual threshold is indicative of better performance on the visual temporal order judgment (vTOJ) task. Black circles represent data points for bilateral CI users; White circles represent data points for bimodal users; White triangles represent data points for unilateral CI users. **3A)** Relationship between the visual threshold and word recognition scores [$r_{10} = -0.87$, $p = 0.0012$]. **3B)** Relationship between the visual threshold and sentence recognition scores [$r_{10} = -0.94$, $p < 0.0001$].

Figure 4. Mean visual threshold of proficient vs. non-proficient performers on auditory speech-recognition tasks. The asterisk (*) denotes a significant difference between groups, at the $p < 0.05$ level, and error bars represent standard error.

Demographic information for each participant including etiology of hearing loss, chronological age, device configuration (BL, bilateral; BM, Bimodal; U, Unilateral), implanted ear(s), pure-tone-average (PTA; dB HL average of the hearing thresholds at 500 Hz, 1000 Hz, and 2000 Hz) for each ear prior to implantation, age at which the participant was diagnosed with a severe-to-profound hearing loss, age at first intervention for hearing loss, age at first implantation, and duration of CI experience. All ages and durations are expressed in years.

Table 1

ID	Etiology	Age at Test	Device Configuration	Implanted Ear	Left PTA	Right PTA	Age at Diagnosis	Age at First Intervention	Age at CI	Duration CI Use	CNC Score	AZ Bio Score	Visual Threshold (ms)
S1	Maternal rubella	43.2	U	Right	108	>110	1.5	1.5	42.1	1.1	42%	53%	46
S2	Connexin 26 mutation	22.5	BL	Bilateral	>110	>110	0	2.4	2.6	19.9	70%	95%	12
S3	Pendred syndrome	24	BM	Left	87	85	5	5	23.6	0.4	56%	71%	27
S4	Connexin 26 mutation	24.4	BL	Bilateral	>110	>110	2	2	2.4	22.1	90%	98%	13
S5	Unknown	32.1	BM	Left	82	72	2.5	2.6	31.5	0.6	98%	100%	9
S6	Unknown	18.2	BL	Bilateral	>115	>115	0	2	1.2	17.0	86%	79%	32
S7	Enlarged vestibular aqueduct	18.7	U	Bilateral	>108	105	3	3	18.1	0.6	46%	64%	49
S8	Unknown	28	BM	Right	100	103	0	1	26.5	1.5	88%	95%	6
S9	Spinal meningitis	29	BM	Right	87	>100	0.7	0.7	28.2	0.8	48%	71%	24
S10	Ototoxic medications	43.9	BL	Bilateral	>100	>102	2	2.5	39.5	4.4	12%	9%	66

Table 2

Correlations between demographic and experimental variables.

	CNC Scores		AzBio Scores		Visual Threshold	
	r_s	p-value	r_s	p-value	r_s	p-value
Left PTA	−0.27	0.45	−0.25	0.49	0.06	0.88
Right PTA	−0.07	0.86	−0.10	0.77	−0.26	0.47
Age at Diagnosis	−0.03	0.93	−0.03	0.93	0.19	0.60
Age at First Intervention	−0.15	0.67	−0.19	0.60	0.34	0.34
Age at Implantation	−0.06	0.88	−0.07	0.85	0.28	0.43
Duration of CI Use	.046	0.19	−0.44	0.20	0.18	0.63

Demographic variables include chronological age, pure-tone-average (PTA; dB HL average of the hearing thresholds at 500 Hz, 1000 Hz, and 2000 Hz) for each ear prior to implantation, age at which the participant was diagnosed with a severe-to-profound hearing loss, age at first intervention for hearing loss, age at first implantation, and duration of CI experience. Experimental variables included perception of CNC words (%), AzBio scores (%), and visual thresholds (ms).