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Relationship between gap detection thresholds and loudness in cochlear implant users

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Abstract

Gap detection threshold (GDT) is a commonly used measure of temporal acuity in cochlear implant (CI) recipients. This measure, like other measures of temporal acuity, shows considerable variation across subjects and also varies across stimulation sites within subjects. The aims of this study were (1) to determine whether across-site variation in GDTs would be reduced or maintained with increased stimulation levels; (2) to determine whether across-site variation in GDTs at low stimulation levels was related to differences in loudness percepts at those same levels; and (3) to determine whether matching loudness levels could reduce across-site differences in GDTs. Thresholds and maximum comfortable loudness levels were measured in postlingually deaf adults using all available sites in their electrode arrays. All sites were then surveyed at 30% of the dynamic range (DR) to examine across-site variation. Two sites with the largest difference in GDTs were then selected and for those two sites GDTs were measured at multiple levels of the DR (10%, 30%, 50%, 70%, and 90%). Stimuli consisted of 500 ms trains of symmetric-biphasic pulses, 40 μ s/phase, presented at a rate of 1000 pps using a monopolar (MP1+2) electrode configuration. To examine perceptual differences in loudness, the selected sites were loudness-matched at the same levels of the DR. Variations in GDTs and loudness patterns were observed across stimulation sites and across subjects. Variations in GDTs across sites tended to decrease with increasing stimulation levels. For the majority of the subjects, stimuli at a given level in %DR were perceived louder at sites with better GDTs than those presented at the same level in %DR at sites with poorer GDTs. These results suggest that loudness is a contributing factor to across-site variation in GDTs and that CI fittings based on more detailed loudness matching could reduce across-site variation and improve perceptual acuity.

Keywords

Auditory prosthesis; loudness matching; electrical hearing; across-site variation; stimulation levels; envelope perception

INTRODUCTION

Most cochlear implant (CI) processors use a temporal code in which the envelopes of speech sounds are extracted and used to amplitude modulate interleaved trains of biphasic pulses.

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Hence, the ability of CI users to resolve temporal-envelope information is crucial for overall performance. It has been shown that the overall success of cochlear implantation may well relate to the extent to which CI recipients are able to process temporal information (Chatterjee and Shannon, 1998; Muchnik et al., 1994). In addition, CI listeners who can capitalize on certain aspects of temporal processing have been shown to have the best speech recognition (Fu, 2002). Therefore, understanding the factors that contribute to temporal processing ability in CI users might have important implications for clinical implant fitting strategies.

Measures of gap detection thresholds (GDTs) have been widely used to assess auditory temporal acuity in CI recipients. Several studies have demonstrated that many CI users exhibit near-normal temporal resolution as measured by psychophysical GDTs along with other temporal measures (Muller, 1983; Shannon, 1983; 1992; Moore and Glasberg, 1988). Nonetheless, GDTs, like other measures of temporal acuity, show considerable variation across subjects (Busby and Clark, 1999). Yet, several studies showed that temporal acuity substantially improved with increasing stimulus level (Preece and Tyler, 1989; Shannon, 1989; Pfingst et al., 2007; Galvin and Fu, 2009).

In electric stimulation, loudness is usually regulated by controlling the amount of charge delivered by each current pulse or current amplitude. When the current amplitude is increased, more nerve fibers are stimulated and the perception of loudness is increased. The growth of loudness, however, occurs at a greater rate than that in acoustic stimulation given that the compression on the basilar membrane is bypassed along with some other cochlear functions (Kiang and Moxon, 1972; Javel and Viemeister, 2000). Consequently, small differences in current level lead to large changes in loudness, which translates into a much smaller dynamic range (DR) than that found in acoustic stimulation (Fourcin et al., 1979). Individual variations with regard to how loudness grows with current has been widely reported and attributed to variations in the spatial distribution of the surviving neurons as well as the distribution of the electrical field (for a review see McKay, 2004).

There are indications that elevated thresholds, abnormal loudness growth, and limited temporal processing are related to the presence of irregularities at the peripheral level (Formby, 1986; Moore, 1996; Moore and Oxenham, 1998; Prosen et al., 1981; Ryan and Dallos, 1975). Currently, there is limited information about the variation in GDTs across stimulation sites; however, early reports indicated that patterns of GDTs vary across sites and subjects (Burkholder-Juhász and Pfingst, 2008). It has been suggested that across-site differences in electrical perception may relate to differences in the local conditions in the cochlea near stimulation sites (Pfingst et al., 2008). Perhaps, if the same mechanisms and pathological processes in the cochlea that mediate loudness (e.g., the number of activated neurons) would similarly affect GDTs, then across-site variation in GDTs would be greatest at low stimulation level. This is possible because regions of the nerve array that are stimulated at low levels are more localized than those stimulated at high levels; therefore, GDTs at low levels would be more subject to effects of localized variation in neural pathology.

The current study was designed to extend previous findings by evaluating the relation between across-site variation in GDTs and loudness percepts at multiple levels of the DR. The first aim of the study was to determine whether across-site variation in GDTs would be reduced or maintained with increased stimulation levels. It was hypothesized that a reduction in across-site variation would occur at higher levels of stimulation based on the idea that spatial extent of neural activation increases at higher stimulus levels and reduces the effects of localized pathologies. Increased spread of excitation should also result in increases in loudness, so there should be a relationship between growth of loudness and

across-site variation in GDTs. The second aim of the study was to determine whether across-site variation in GDTs at low stimulation levels (30% DR) is related to differences in loudness percepts and the third aim was to determine whether matching loudness levels across the tested sites would reduce across-site differences in GDTs.

METHODS

Subjects

Nine postlingually deaf subjects (6 males and 3 females) participated in this study. One subject had a Nucleus CI24M (Straight array) implant, six had CI24R(CS) (Contour), and two had CI24RE (Freedom) implants: the CI24M is a straight electrode array with band-type electrodes encircling the silicone-rubber carrier; the CI24R (CS) and CI24RE implants are contoured to match the curvature of the scala tympani and they have electrodes located on the medial side of the curved carrier. Subjects ranged from 51 to 69 years of age. All subjects had at least 12 months of experience with their implants. Subjects' demographics are given in Table 1. All subjects were compensated for their participation. The use of human subjects in this study was reviewed and approved by the University of Michigan Medical School Institutional Review Board.

Electrical stimulation hardware

To assure uniformity in the external hardware, laboratory SPrint® (for CI24M and CI24R(CS) implants or Freedom® (for CI24RE implants) processors (Cochlear Corporation, Englewood, CO, USA) were used. Communication with the processors was controlled using custom software run on a PC. Sequences of frames were generated and sent to the processors via Cochlear NIC II (Nucleus Implant Communicator) software (Swanson, 2004). All testing was conducted inside a large, carpeted double-walled sound-attenuating chamber with low reverberation to ensure a uniform testing environment across subjects and sessions. Subjects were seated in the center of the room facing a testing monitor with a keyboard and a mouse to enter their responses directly.

Electrical stimuli

All stimuli were delivered directly to the subject's implanted receiver/stimulator by software control of the external processor. No acoustic stimulation was used. Stimuli were 500 ms trains of symmetric biphasic pulses of with phase duration of 40 μ s and an interphase gap of 8 μ s presented at a rate of 1000 pulses/s. A monopolar (MP1+2) electrode configuration was used. Current levels were varied in the implant manufacturer's Current Level Units (CLUs), where a 1 CLU step equaled 0.1759 dB of current for the CI24M and CI24R(CS) implants and 0.1569 dB for the CI24RE implants.

Psychophysical procedures

a. Measurements of T and C levels—Absolute detection thresholds (T levels) and maximum comfortable loudness levels (C levels) were obtained using the method of adjustment in which the subjects adjusted the level of the stimulus by using a computer mouse and a GUI controlled by custom software. The stimulus burst duration was 500 ms with silent intervals of 1700 ms on average in between bursts. For T levels, listeners adjusted the level until the stimulus was barely audible. For C levels, subjects adjusted the level of the stimulus to the loudest level that they believed they could tolerate for a long period without discomfort. These measurements were obtained three times for each available site in the subjects' electrode array. In this work, the term “stimulation site” is used to label the stimulation between a given active scala tympani electrode and the extracochlear electrode. DR for each site was calculated as the difference in current level between the

mean T level and the mean C level measurements. The average range of the three repeated measures per site was calculated across subjects. For the T level the average range was 4 ± 1.8 CLU and for the C level the mean was 3.2 ± 1.6 CLU.

b. Gap detection thresholds—GDTs were obtained at 30% of the DR using a two-interval forced choice paradigm with flanking cues. On each trial, subjects were presented with four sequential stimuli with interstimulus duration of 500 ms. The first and fourth stimuli consisted of continuous pulse trains which served as flanking cues. One of the remaining two intervals, chosen at random on each trial, also contained this continuous signal while the other interval contained a noncontinuous pulse train with a gap near the middle. Subjects were asked to identify the interval that sounded different from the other three intervals. Feedback was provided after each trial. For the noncontinuous pulse train, gaps were created after approximately 250 ms of the 500 ms train. These gaps were generated by omitting pulses, starting at an initial value of 25 missing pulses. A two-down one-up adaptive tracking procedure (Levitt, 1971) was used. Each run was terminated after 14 reversals were obtained and GDTs were defined as the average of the number of missing pulses at the last 8 reversals. Gap duration was decremented or incremented by 5 pulses until a first reversal occurred; after the first reversal a step size of 2 pulses was used to the fourth reversal and then a 1 pulse step size was used to the last reversal.

Using this procedure, GDTs were measured for all enabled electrodes in the subject's electrode array in a random order. These initial measurements across all sites were made to identify two sites with the largest difference in GDTs. For the two selected sites, GDTs were measured at 10%, 30%, 50%, 70%, and 90% of the DR in a random order. A total of 5 repetitions were obtained for each of the 10 experimental conditions (2 sites times 5 levels) using a different randomization each time. GDT mean and standard deviation values were calculated.

c. Loudness matching—In this procedure, listeners were asked to loudness match two stimuli, standard and reference, at multiple levels of the DR of the reference stimulus (10%, 30%, 50%, 70%, and 90%). Both of the two selected sites, one with the better GDTs (Site A) and one with the poorer GDTs (Site B), served as the standard and the reference stimulus. Specifically, Site A (standard) was loudness-matched to Site B (reference) at DRs of site B and Site B (standard) was loudness-matched to Site A (reference) at respective DRs of site A.

A total of three measurements was obtained for each of these conditions at each level of the DR in a random order. Listeners were asked to first listen to the reference stimulus and then to listen to the standard stimulus and, if needed, adjust the level of the standard stimulus using either 1 or 5 CLU steps until a loudness match was achieved. Subjects were not limited in the number of times they could listen to each of the standard and the reference stimuli. Stimuli were 500 ms continuous pulse train with 1000 ms interstimulus duration presented at a stimulation rate of 1000 pulses/s. Values collected from these measurements were plotted as a function of the reference-stimulus levels to show differences in loudness percepts across the two sites as illustrated in the Results section.

d. GDTs for loudness-matched sites—In a follow-up experiment using a subset of the subjects, a third round of GDTs was measured at the two selected sites. The purpose of this experiment was to determine whether loudness matching could reduce across-site differences in GDTs. As such, GDTs were re-measured for the better site (A) and the poorer site (B) using the loudness-matched levels obtained with the procedure described in section “c” above. To demonstrate the differences in loudness percepts between the two sites, the loudness-matched levels in CLUs obtained for each of the better and poorer sites were

converted to percent DR and plotted in Figure 2. The following equation was used in this conversion:

$$\%DR = (L_p - T_p / C_p - T_p) 100$$

where L_p is the level at the standard site in current level units (CLUs) that was loudness matched to a selected level in % DR at the reference site; C_p and T_p are the C and T levels at the standard site in CLUs. GDTs were measured at the better and the poorer sites using the loudness-matched levels when each served as the reference stimulus.

RESULTS

Across-site differences in GDT-versus-level functions

In Figure 1 and Table 2, GDTs measured from the two selected sites for each subject are shown as a function of level in percent of the DR of the reference site. For each of these conditions, means and standard deviations of five repeated measures are displayed. Separate analyses were conducted for each subject because the main interest was to examine across-site differences in GDTs within subjects. GDT data collected from each subject were analyzed using a two-way repeated measure ANOVA with *site of stimulation* (poorer, better) and *stimulation level* (10%, 30%, 50%, 70%, 90% of the DR of the stimulated site) as the within-subject variables. An α criterion of 0.05 was used to determine statistical significance in the omnibus F tests. All *t*-tests reported below were corrected for multiple comparisons using an adjusted *p*-value criterion of 0.01. Results from these analyses are summarized below for all subjects.

A significant main effect of site of stimulation ($p < 0.05$) was found for six of the 9 participants (S60, S67, S69, S77, S80, and S81): GDTs were lower for the better sites than that for the poorer sites. The remaining three participants (S45, S71, and S79) did not show statistically significant differences in GDTs across the two selected sites. In addition, the main effect of stimulation level was also significant ($p < 0.05$) for all subjects. As can be seen in Figure 1, all of the subjects performed better at high stimulation levels than at low levels and an asymptote at a GDT near 1 ms was reached in some cases. Post-hoc *t*-tests were conducted to compare GDTs at the different stimulation levels (10%, 30%, 50%, 70%, 90% of the DR) using the means of the data for the two stimulation sites at each level. These results showed that the means of the GDTs measured from the two selected sites improved when stimulation level was increased ($p < 0.01$). The improvement in GDTs, however, saturated at different stimulation levels for different subjects. Specifically, the means of the GDTs for the two sites did not improve significantly for some subjects at levels higher than 50% of the DR (S69, S71, S80 and S81). Interestingly, the mean GDTs did not improve significantly above 30% of the DR for S45. Yet, for four other subjects 70% of DR was required to achieve maximum average performance (S60, S67, S77, and S79). Average GDTs for S79 were similar when stimulus levels were 30% and 50% of the DR.

Statistical analyses further revealed that for those subjects who showed a significant main effect of site of stimulation (S60, S67, S69, S77, S80, and S81), there was also a significant interaction between site of stimulation and level ($p < 0.05$). These results suggest that across-site GDT differences were indeed dependent on stimulation level. Data were subjected to post-hoc analyses to determine the levels at which GDTs were different across the two sites. Significant differences ($p < 0.01$) are marked in Figure 1 with an asterisk. In general, across-site differences in GDTs were robust at low stimulation levels and weakened at relatively high levels. For subjects who showed significant differences in GDTs between the two sites at low stimulation levels, these differences became statistically non-significant

at higher levels: 50% DR for S69 and S81; and 70% DR for S60, S67 and S80. For S77, the statistically significant across-site differences persisted even at 90% DR. These results suggest that, in general, the improvement in GDTs as a function of level was slower for the poorer sites and that higher stimulation levels are needed to improve GDTs at these poor sites relative to performance at the better sites.

Relative loudness growth across sites with contrasting GDTs

Loudness-matched levels for the two selected sites are shown for each subject in Figure 2. The sites with the better GDTs are on the ordinates and the sites with the poorer GDTs are on the abscissa. Each site served sequentially as the reference stimulus while the other site served as the standard. The shaded symbols represent the loudness-matched levels when the site with poorer GDTs served as a reference and the open symbols represent the loudness-matched levels when the site with better GDTs served as a reference stimulus. The diagonal line represents a zero difference in loudness between the two sites. Consequently, points below the diagonal line indicate lower average loudness at the poorer site and points above the diagonal line indicate lower average loudness at the better site. In general, loudness for the poorer site grew more slowly at low levels but then grew more rapidly at higher levels so that the largest differences in loudness were somewhere near the middle of the DR. Near the T and C levels, the loudness of the two sites was usually approximately equal.

As Figure 2 shows, there appeared to be some perceptual differences in loudness growth across the two sites that had different GDTs. Specifically, stimuli at a given level in %DR were often perceived as softer at sites with poorer GDTs than at sites with better GDTs. In addition, the loudness-growth patterns seemed to be subject-specific. Note that the subject with the largest differences in loudness between the two sites (S77 in Figure 2), also had the largest differences in GDTs between these two sites (S77 in Figure 1). For this subject, loudness growth at the poorer-GDT site (Site 6) was slow at low levels and then rapid at the highest tested levels. Four other subjects (S67, S79, S80 and S81) had pronounced slower loudness growth at low levels but recovered with higher growth rates above 30% or 50% of the DR of the poorer site. Three of these subjects (S67, S80 and S81) also had significantly poorer GDTs at the poorer site at low levels ($p < 0.01$) but similar GDTs for the two sites at higher levels. One subject (S71) had close to equal loudness at both tested sites and no significant differences in GDTs between the two sites. Two subjects (S60 and S69) showed slightly greater loudness for the poorer site at some levels near the middle of the DR, and GDTs that were significantly different only at low levels in the DR. The remaining subject (S45) showed softer loudness perceptions peaking around 70% of the DR of the site that had poorer GDTs as determined by the original GDT measurements across all sites. However, this subject showed no appreciable differences in GDTs at any tested level in the DR, when the two selected sites were examined more extensively in the second phase of the experiment (data in Figure 1 and Table 2).

Comparison of GDTs at loudness-matched levels

GDTs for the poorer and the better sites are shown in Figure 3 for a subgroup of subjects (S60, S67, S77, and S81). Differences in performance between the better and poorer sites are shown in the left column; these data are adopted from Figure 1. Effect of loudness matching on GDTs across the poorer and the better sites is demonstrated in the middle and the right columns, respectively. In the middle column, GDTs for the poorer site are shown as a function of level in percent of DR of the poorer site (darkly-shaded circles as in the left column) and compared to GDTs as a function of levels matched in loudness to the loudness of the better site at various percentages of the DR of the better site (lightly-shaded circles). In the right column, GDTs for the better site are shown as a function of level in percent DR of the better site (open triangles as in the left column) and compared to GDTs as a function

of levels matched in loudness to the loudness of the poorer site at various percents of the DR of the poorer site (shaded triangles).

In order to determine whether loudness matching reduced across-site differences in GDTs by improving performance on the poorer site, GDT data from the poorer site were subjected to a two-way ANOVA with main effects of loudness matching (unadjusted levels, loudness-matched levels) and stimulation level (10%, 30%, 50%, 70%, 90% of the DR) as the within-subject variables. GDTs for the better site obtained using unadjusted and loudness-matched levels were subjected to a similar analysis to demonstrate the effect of random loudness balancing. An α criterion of .05 was used to determine statistical significance in the omnibus F tests. All *t*-tests were corrected for multiple comparisons using a Bonferroni correction. Data analyses were conducted separately for each subject.

Results showed significant improvement in GDTs at the poorer sites when loudness-matched levels to that at the better sites were used. This improvement was noticeable at low to mid levels of the DR. At the higher levels of the DR, there were no significant differences in GDTs across the loudness matched versus unmatched conditions. These results were consistent for three subjects (S67, S77, and S81). For S60, a similar improvement in GDTs can be seen in Figure 3, however, this improvement failed to reach statistical significance.

Results further showed that there were significant differences in GDTs for the better sites using unadjusted levels versus levels loudness-matched to loudnesses at the poorer sites. When using loudness-equated levels to those at the poorer sites, GDTs for the better sites weakened. This perhaps was due to the fact that softer levels were used since the better sites seemed to be perceived louder than the poorer sites. This was demonstrated for three subjects (S60, S67 and S77) at low to mid levels of the DR. For one subject (S81), manipulating these levels did not significantly affect the GDTs.

DISCUSSION

GDTs in electric hearing have been previously addressed and its relation to variables such as stimulus level or frequency has been examined (e.g. Preece and Tyler, 1989; Shannon 1989). This study expands our understanding of this measure by probing the relation between GDTs and loudness within channels of stimulation within individuals. Understanding the relationships between GDTs, loudness, and stimulation site, may facilitate efforts to improve temporal acuity by adjusting level parameters for individual stimulation sites in processor-fitting strategies.

Across-site variation in GDTs

Results of this study demonstrated significant differences in GDTs across sites of stimulation within the majority of listeners. From previous studies on gap detection and other forms of envelope detection by cochlear implant users, it is evident that the pattern for this variation along the tonotopic axis is not consistent across subjects (Pfingst et al., 2008; Burkholder-Juhasz and Pfingst, 2008). These results suggest that the across-site pattern of GDTs is subject-specific and thus perhaps a result of local subject-specific variation in conditions along the implanted electrode array.

In agreement with previous studies (Preece and Tyler, 1989; Shannon 1989; Chatterjee et al., 1998; Hanekom and Shannon 1998), current results demonstrated that GDTs improved with increasing stimulation level. This improvement in GDTs reached an asymptote at mid to high stimulation levels. Some differences were noted across subjects, which could be related to differences in loudness perception as a function of current level. Consistent with this study hypothesis, results from the current work showed that by increasing stimulation

level, across-site differences in GDTs were reduced. As can be seen in Figure 1, the largest differences in performance between the poorer and better sites occurred at low stimulation levels.

Stimulation at low levels is likely to activate a small number of neural fibers; hence, across-site variation will be greater reflecting the local conditions of sites adjacent to place of stimulation. With increasing stimulation level, there is a greater spread of excitation along the tonotopic axis of the cochlea (Bierer and Middlebrooks, 2002; Snyder et al., 2004). It is possible that larger current spread can reduce much of the across-site variation by stimulating remote regions which may have a denser population of neural fibers and, therefore, surmounting differences in local conditions in the nearby sites. While this could be true in most of the cases tested here, it might not apply to all CI users. For example, S77 (shown in Figure 1) maintained across-site differences in GDTs even at the highest stimulation level used in this study. It is of interest to note that S77 had the earliest onset of deafness and the longest duration of deafness before implantation among the subjects in this study (see Table 1). A negative correlation between GDTs and age at onset of deafness has been previously reported (Busby and Clark, 1999). This might be due to greater and more widespread neural pathology in early-deafened subjects; hence, increased stimulation levels might not fully overcome this problem for some stimulation sites.

Across-site variation in loudness perception and relation to GDTs

One of the main goals of the current work was to determine whether across-site differences in GDTs were related to across-site differences in loudness. In Figure 2, different patterns of relative loudness perception between two tested sites can be noted across subjects. More important, results showed that there were perceptual differences in loudness between the two sites suggesting a relationship between GDTs and loudness. This relationship can be described such that stimuli at a given level were perceptually judged to be louder at sites with better GDTs than at sites with poorer GDTs. These relationships were seen primarily in the middle regions of the DR and were observed for the majority of the subjects except for two subjects (S45 and S79) who showed minimal GDT differences but some differences in loudness across the two sites. These results suggest that loudness can contribute to the across-site variations in GDTs but it does not account for all of the observed variation in performance across individuals or across stimulation sites. Perhaps, these results underline the unpredictability of individual differences among CI users and further suggest the dependence of GDTs on other factors such as cognitive elements (van Wieringen and Wouters, 1999).

Overall, results seem to be consistent with the idea that across-site differences in GDTs might reflect localized variations along the length of the implanted cochlea. It has been suggested that loudness is related to the amount of neural activity evoked in the auditory nerve and that the magnitude of current level reaching the neurons is related to the distance between stimulation sites and the place of neural activation (Cohen et al., 2003). As such, the greater this distance, the greater the current needs to be in order to achieve a given level of loudness. Variations in nerve survival and/or the condition of the surviving neurons along the electrode array perhaps can contribute to differences in loudness percepts such that the better site would require less current to reach a specific loudness level than that required for the poorer site. Deafness and implant-related pathology can affect both sensitivity and temporal properties of auditory neurons (Shepherd and Javel, 1997), which might explain the relationship between GDTs and loudness perception.

A further interest in this study was to examine whether loudness matching across stimulation sites would reduce across-site differences in GDTs. Indeed, results from the follow-up experiment suggest that loudness matching across the poorer and the better sites can reduce

across-site differences in GDTs to some extent. However, the reduced across-site variation resulted in either improvement or worsening of GDTs depending on the performance of the site which was selected to be the standard site. Specifically, as shown in Figure 3, GDTs at the poorer sites improved when levels were matched in loudness to levels at the better sites. Alternatively, GDTs were relatively higher (worse) for the better sites when loudness levels were matched to that at the poorer sites. These findings suggest that across-site differences in loudness perception can contribute to across-site differences in GDTs. In addition, current results suggest that it is perhaps important to assess the psychophysical performance of the sites to be tested prior to loudness matching as it is typical in the field to perform the latter prior to any psychophysical measures. While loudness matching prior to GDT measurements can minimize any level differences, it can, however, impact the performance of some of the better sites if the differences in performance were not taken into account.

The important topic of a relation between a psychophysical measure and loudness percepts within sites of stimulation needs to be similarly addressed in future studies to determine whether this relation can be seen with other temporal measures as well. Overall, several studies have found that increasing stimulation level leads to marked improvement in performance on a wide range of other temporal measures such as modulation detection (Shannon, 1992; Galvin and Fu, 2005; Pfingst et al., 2007), pulse rate discrimination (Pfingst et al., 1994), and modulation-frequency discrimination (Morris and Pfingst, 2000). If performance on these temporal measures can also be improved by adjusting level parameters at the poorer sites (see below), this suggests that it is possible to improve temporal acuity in CI recipients, which might be particularly beneficial to those who receive limited benefits from their implant prosthesis.

Clinical implications

Data from these experiments suggest a relation between GDTs and loudness percepts within stimulation sites. If the mechanisms underlying improvement of GDTs as a function of level are related to loudness percepts, then examining the latter might improve temporal gap detection in CI users. There is a growing body of evidence suggesting a relation between GDTs and speech recognition (Muchnik et al., 1994; Sagi et al., 2009). Hence, the extent to which CI recipients are able to resolve temporal information, including their ability to detect a silent gap, should be maximized with the expectation that their speech performance would also improve.

Of particular interest here is that some studies have shown that speech recognition can be improved in CI recipients when stimulation levels are increased in the speech processor maps. Primarily, these studies focused on increasing the stimulation levels by raising the T levels in the processor maps globally for all electrodes (Skinner, et al., 1997; 1999). Alternatively, stimulation levels were also increased by compressing the DR where the T and C levels were equated for each electrode pair (Franck, et al., 2002). Although an improvement in performance was observed for some subjects in these studies, variation across stimulation sites within subjects is well documented and needs to be taken into account (Pfingst and Xu, 2004; Pfingst et al., 2004; Burkholder-Juhasz and Pfingst, 2008; Pfingst et al., 2008). Therefore, it should be considered that adjustment of stimulation levels on a site-by-site basis might provide a better approach to improve speech recognition. Specifically, a potential strategy for improving GDTs and speech recognition would be to modify the processor input-output functions on sites with poor GDTs to achieve loudness growth functions matching those at sites with good GDTs. Overall, the present findings underscore the importance of loudness measures in the clinical realm and further call for the importance of establishing a psychophysical measure in the clinic to assess performance across all available sites in the patient electrode array. Typically, loudness matching is performed in an orderly manner. If the better performing sites are loudness-matched to the

poor performing sites, this might not be advantageous. These important issues remain a motivation for future studies.

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List of abbreviations

CI	Cochlear implant
GDT	Gap detection threshold
DR	Dynamic range
NIC2	Nucleus Implant Communicator 2® software
CLUs	Current level units
T level	Detection threshold level
C level	Maximum comfortable loudness level

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Figure 1.

GDTs (mean $\pm$ SD) are shown as a function of stimulation level in percent of the DR for each site. Each panel displays data collected from a different participant whose subject numbers are shown at the top of the panel. Filled symbols represent sites with poorer GDTs and open symbols represent sites with better GDTs based on the results shown in Figure 1. An asterisk represents significant differences between poorer and better sites.

Figure 2.

Loudness-matched levels for the two selected sites with poorer and better GDTs are plotted. The poorer sites are represented on the abscissa and the better sites are represented on the ordinate. Each site served once as a standard and once as a reference stimulus in separate tests. A total of three measurements was obtained for each condition and the mean and the range are shown. The filled symbols and dotted lines represent the loudness-matched levels when the site with poorer GDTs served as the reference stimulus and the open symbols and dashed lines represent the loudness-matched levels when the site with better GDTs served as the reference stimulus. The diagonal line represents a zero difference in loudness between the two selected sites.

Figure 3.

GDTs (mean $\pm$ SD) are shown as a function of percent of DR (as detailed below) for four subjects. For each subject, data from Figure 1 are replotted in the left column for comparison. In the middle column, GDTs are shown for the poorer site by comparing those shown in the left column (darkly-shaded circles) with GDTs obtained using simulation levels that were matched in loudness to levels in % DR at the site with better GDTs (lightly-shaded circles). Similarly, in the right column, GDTs for the better sites are shown using the better sites respective levels in % DR (open triangles) and at levels matched in loudness to levels in % DR at the poorer site (shaded triangles). The asterisks represent statistically significant differences in GDTs at the indicated levels.

Table 1

Subject information

Subject	Gender	Age	Onset of Deafness	CI use (years)	Implant type	Strategy	Etiology of deafness
S45	M	52	44	7	CI24R(CS)	ACE	Head trauma
S60	M	69	62	5	CI24R(CS)	ACE	Hereditary
S67	M	67	59	8	CI24R(CS)	ACE	Hereditary
S69	M	68	61	4	CI24M	ACE	Hereditary
S71	M	62	57	5	CI24R(CS)	ACE	Unknown
S77	M	58	3	3	CI24R(CS)	ACE	Hereditary
S79	F	51	45	6	CI24R(CS)	ACE	Meningitis
S80	F	55	35	2	CI24RE	ACE	Unknown
S81	F	58	52	3	CI24RE	ACE	Hereditary

Table 2

Average GDTs (± 1 SD) in ms

		S45		S60		S67	
DR	Site 3	Site 9	Site 5	Site 20	Site 6	Site 12	
10%	22.1 $\pm$ 14	19.6 $\pm$ 10.3	32.4 $\pm$ 6.4	48.4 $\pm$ 11.1	55.7 $\pm$ 21.9	34.5 $\pm$ 9.1	
30%	8.7 $\pm$ 2.5	7.8 $\pm$ 2.9	16.2 $\pm$ 5.3	38.0 $\pm$ 9.7	48.4 $\pm$ 21.2	18.6 $\pm$ 4.4	
50%	4.9 $\pm$ 0.9	5.5 $\pm$ 0.9	4.6 $\pm$ 0.7	17.3 $\pm$ 4.9	24.5 $\pm$ 4.3	6.2 $\pm$ 1.5	
70%	4.1 $\pm$ 0.9	4.7 $\pm$ 0.9	2.3 $\pm$ 0.1	3.4 $\pm$ 0.9	8.7 $\pm$ 2.1	1.6 $\pm$ 0.5	
90%	3.4 $\pm$ 0.3	2.5 $\pm$ 0.6	1.5 $\pm$ 0.1	1.5 $\pm$ 0.5	1.9 $\pm$ 0.7	1.5 $\pm$ 0.4	

		S69		S71		S77	
DR	Site 4	Site 9	Site 5	Site 22	Site 6	Site 15	
10%	24.4 $\pm$ 4.9	39.0 $\pm$ 16.3	25.5 $\pm$ 21.0	34.6 $\pm$ 20.5	38.9 $\pm$ 9.1	34.9 $\pm$ 5.9	
30%	7.0 $\pm$ 7.7	22.7 $\pm$ 4.4	9.2 $\pm$ 5.1	19.5 $\pm$ 6.3	38.9 $\pm$ 4.7	9.3 $\pm$ 3.5	
50%	1.3 $\pm$ 0.2	5.7 $\pm$ 2.4	4.7 $\pm$ 3.0	5.0 $\pm$ 2.4	33.0 $\pm$ 8.2	3.2 $\pm$ 0.5	
70%	1.5 $\pm$ 0.4	1.4 $\pm$ 0.3	3.0 $\pm$ 2.2	1.8 $\pm$ 1.2	20.7 $\pm$ 7.8	1.5 $\pm$ 0.2	
90%	1.4 $\pm$ 0.6	1.2 $\pm$ 0.3	1.8 $\pm$ 1.3	1.1 $\pm$ 0.7	9.6 $\pm$ 1.3	0.5 $\pm$ 0.1	

		S79		S80		S81	
DR	Site 16	Site 20	Site 3	Site 17	Site 10	Site 17	
10%	51.4 $\pm$ 8.5	49.9 $\pm$ 18.7	45.4 $\pm$ 9.8	24.3 $\pm$ 7.2	36.0 $\pm$ 12.1	18.2 $\pm$ 6.4	
30%	25.8 $\pm$ 5.9	32.5 $\pm$ 6.6	40.2 $\pm$ 7.0	3.7 $\pm$ 0.6	13.7 $\pm$ 3.3	1.9 $\pm$ 0.3	
50%	26.8 $\pm$ 20.2	31.4 $\pm$ 7.6	12.4 $\pm$ 2.9	1.3 $\pm$ 0.2	2.6 $\pm$ 0.6	0.6 $\pm$ 0.1	
70%	8.2 $\pm$ 3.1	21.1 $\pm$ 7.6	2.9 $\pm$ 0.7	0.7 $\pm$ 0.1	0.8 $\pm$ 0.2	0.6 $\pm$ 0.1	
90%	4.9 $\pm$ 0.8	8.8 $\pm$ 2.6	2.2 $\pm$ 0.2	0.5 $\pm$ 0.0	0.5 $\pm$ 0.1	0.5 $\pm$ 0.1	