Research Article

Effect of Pulse Rate on Loudness Discrimination in Cochlear Implant Users

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ABSTRACT

Stimulation pulse rate affects current amplitude discrimination by cochlear implant (CI) users, indicated by the evidence that the JND (just noticeable difference) in current amplitude delivered by a CI electrode becomes larger at higher pulse rates. However, it is not clearly understood whether pulse rate would affect discrimination of speech intensities presented acoustically to CI processors, or what the size of this effect might be. Intensity discrimination depends on two factors: the growth of loudness with increasing sound intensity and the loudness JND (or the just noticeable loudness increment). This study evaluated the hypothesis that stimulation pulse rate affects loudness JND. This was done by measuring current amplitude JNDs in an experiment design based on signal detection theory according to which loudness discrimination is related to internal noise (which is manifested by variability in loudness percept in response to repetitions of the same physical stimulus). Current amplitude JNDs were measured for equally loud pulse trains of 500 and 3000 pps (pulses per second) by increasing the current amplitude of the target pulse train until it was perceived just louder than a same-rate or different-rate reference pulse train. The JND measures were obtained at two presentation levels. At the louder level, the current amplitude JNDs were affected by the rate of the reference pulse train in a way that was consistent with

greater noise or variability in loudness perception for the higher pulse rate. The results suggest that increasing pulse rate from 500 to 3000 pps can increase loudness JND by 60 % at the upper portion of the dynamic range. This is equivalent to a 38 % reduction in the number of discriminable steps for acoustic and speech intensities.

Keywords: cochlear implant, stimulation pulse rate, loudness discrimination, loudness variability

INTRODUCTION

Cochlear implants (CIs) are a very successful intervention to treat sensorineural deafness. However, speech perception outcomes are generally poor particularly in adverse listening environments and vary significantly across implanted patients. One important parameter in CI fitting is stimulation pulse rate, the number of electric current pulses that are delivered per unit time by the intra-cochlear electrodes. In a typical CI processing, the envelope of energy variations in each acoustic frequency-band modulates the level of current pulses on the corresponding electrode. Higher pulse rates allow more accurate presentation of envelope details over time, which should conceivably result in better representation of envelope cues. However, reception of envelope information by CI users relies on their sensitivity to changes in envelope intensity and may not be necessarily better at higher pulse rates. There is no doubt that clinical fitting of CIs and development of

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new stimulation strategies can benefit from more knowledge about how stimulation parameters affect perception of cues that are known to be important for speech understanding. Contributing to that knowledge base is a central goal of the present study. The focus is on the effect of stimulation pulse rate on the just noticeable difference (JND) in sound intensity, i.e., the smallest acoustic intensity increment that is noticeable by CI users.

The JND in the level of a sound can be modeled as the smallest level increment that results in a noticeable change in loudness percept (Durlach and Braida, 1969). In CI users, the transformation between acoustic intensity and loudness occurs in two stages. In the first stage, sound intensity is mapped to the amplitude of current pulses on implant electrodes by a function that is implemented in speech processors. The second stage is the psychophysical transformation between current amplitude and loudness. Hence, the JND in acoustic intensity (acoustic intensity JND) depends on both the acoustic-to-electric mapping in implant device settings and the smallest increase in current amplitude required for a noticeable loudness change. The latter is the JND in electric current amplitude (or current amplitude JND).

There is evidence that current amplitude JNDs become larger at higher pulse rates (Kreft et al., 2004a; Galvin and Fu, 2009). This effect of pulse rate on current amplitude JND may be mediated by two different factors. One factor is that the growth of loudness with current amplitude becomes slower as pulse rate is increased (Kreft et al., 2004b; Zhou et al., 2012). With a slower loudness growth, a larger increment in current amplitude would be required for a given loudness increment. The other factor that may mediate the observed effect of pulse rate on current amplitude JND is that loudness JND (which is the smallest noticeable loudness increment) may become larger at higher pulse rates. With a larger loudness JND, a larger increment in loudness (and therefore a larger increment in current amplitude) would be required for a noticeable loudness change.

We hypothesized that loudness JND is affected by stimulation pulse rate. The ability of CI users to discriminate loudness differences may become poorer at higher pulse rates due to a greater degree of noise in the sensory and neural representation of higher-rate pulse trains. According to signal detection theory, loudness discrimination of two auditory stimuli is inversely related to the variability or noise in loudness perception when the same auditory stimuli are presented many times (Green and Swets, 1966). As pulse rate is increased, peripheral auditory neurons respond less regularly and more stochastically to individual pulses of pulse trains, perhaps due to neural mechanisms such as refractoriness, adaptation,

and response facilitation (Zhang et al., 2007; Hu et al., 2010; Woo et al., 2010; Boulet et al., 2015). More stochastic and asynchronous neural spikes in response to a fixed stimulus intensity may contribute to greater noise at the central auditory processing levels, possibly resulting in greater loudness variability and larger loudness JND.

The JND in loudness percept (loudness discrimination ability) has important practical implications for perception of sound intensity cues. Loudness JND is inversely related to the number of loudness JND steps within a loudness range (the number of JND steps becomes smaller when JND values become larger), and the number of loudness JND steps is identical to the number of acoustic intensity JND steps or acoustic intensity resolution (Allen and Neely, 1997). Therefore, loudness JND is inversely related to the number of acoustic intensity JND steps or acoustic intensity resolution. For CI users, it can be demonstrated that the number of acoustic intensity JND steps is only related to loudness JND and is irrelevant to the acoustic-to-electric mapping in CI processors (see the Appendix). If pulse rate affects loudness JND, it would necessarily affect the number of acoustic intensity steps or intensity resolution. On the other hand, the effect of pulse rate on the growth of loudness with current amplitude would not necessarily translate to changes in acoustic intensity JNDs. Shallower loudness growth at higher pulse rates can be compensated by a steeper acoustic-to-electric mapping in CI processors such that acoustic intensity JNDs remain unchanged. Thus, pulse rate could impair sensitivity to acoustic intensity cues only if it affects loudness JND.

The effect of stimulation pulse rate on loudness JND can be assessed by measuring current amplitude JNDs, provided that pulse rate effect on the growth of loudness with current amplitude is accounted for. One way is to convert current amplitude JNDs to loudness JNDs using a precise estimate of loudness growth functions (the functions that relate current amplitude to loudness). However, the non-linear and subject- and electrode-specific loudness growth functions are not easy to obtain (McKay and McDermott, 1998). This study used an approach based on signal detection theory that does not require any knowledge about loudness growth functions. Current amplitude JNDs were measured for two equally loud pulse trains by comparing the loudness of each target pulse train to the loudness of a same-rate or different-rate reference pulse train. The pattern of current amplitude JNDs obtained with different combinations of pulse rates for target and reference stimuli were used to evaluate the effect of pulse rate on loudness JND. The results support the hypothesis that loudness JND becomes larger at higher stimulation pulse rates.

METHODS

Subjects

Ten implanted ears from eight CI user participants were tested in this study (two bilateral users were tested on both implanted ears). The participants were post-linguistically deafened adult users of Freedom Cochlear Nucleus implants and had been using their device for at least one year at the time of testing. Subject recruitment and testing was approved by the New York University School of Medicine's Internal Review Board (IRB) and consent was obtained for each participant.

Experiments

Current amplitude JNDs were obtained for pulse trains of 500 and 3000 pps (pulses per second) presented to a single electrode in four different experiment conditions. The experiment conditions A to D are shown in panels a to d of Fig. 1, respectively. For each condition, the current amplitude JND of the target pulse train was the difference between target levels that corresponded to approximately 80 and 50 % probability of the target being identified louder than a reference pulse train (A_{80} and A_{50} , respectively). The A_{80} target level corresponds to the target being perceived just louder than the reference. The A_{50} target level corresponds to the target being perceived equally loud as the reference. The reference pulse train was either at the same rate as the target (conditions A and B) or was at a different rate (conditions C and D). The experiment conditions are specified by the rates of the reference and target pulse trains. The below section discusses the

theoretical model behind the design of the four experiment conditions and describes how the current amplitude JND results can be used to compare loudness JNDs for the two pulse rates.

The Theory Behind Current Amplitude JND Measures

Loudness perception of an auditory stimulus varies in different presentations of the exact same stimulus and can be modeled by normal distribution identified by mean and standard deviation. Schematics of loudness distributions of reference and target pulse trains for the four experiment conditions A to D are shown by the probability-versus-loudness plots in panels a to d of Fig. 2, respectively. Solid (green) and dashed (red) curves are the normal distributions of reference and target pulse trains respectively. The mean reference loudness is shown by L_{Ref} . The mean target loudness is shown by L_{80} and corresponds to 80 % probability of the target being identified louder than the reference (target being perceived just louder than the reference). The L_{50} target level corresponds to 50 % probability of target being identified louder than the reference and is thus equal to the reference loudness L_{Ref} . The variances of the loudness distributions are shown by arrows. The variance is larger for the 3000-pps than the 500-pps pulse train in these schematics, consistent with the hypothesis that loudness variability is greater for higher-rate pulse trains. According to signal detection theory (Green and Swets, 1966), the difference between L_{80} and L_{50} can be described as $\Delta L = d' \sqrt{\frac{1}{2}(\delta_T + \delta_R) + \delta_C}$. The constant d' is the sensitivity index, δ_T and δ_R denote

A (Target: 500pps , Reference : 500pps)

B (Target: 3000pps , Reference: 3000pps)

C (Target: 500pps , Reference: 3000pps)

D (Target: 3000pps , Reference: 500pps)

Fig. 1. Schematics of target and reference pulse trains for the four experiment conditions **A** to **D**, respectively. The current amplitude JND for each condition is the difference between target levels corresponding to 80 and 50 % probability of target being identified louder than the reference

Fig. 2. The hypothetical loudness distributions of target and reference stimuli for the four experiment conditions **A** to **D**, respectively. Each loudness distribution is identified by its mean and variance. The plots are based on the hypothesis that loudness variability δ is larger for the higher-rate pulse train. The JND in loudness between target and reference (ΔL) is proportional to the loudness variabilities of target and reference stimuli. The hypothetical current amplitude JND of the target stimulus are shown in the loudness-versus-amplitude plots for the experiment conditions **A** to **D**. The current amplitude JND is contributed by both the

mean loudness difference between target and reference (ΔL) and the slope of the target's loudness growth function. The loudness growth functions are plotted based on the hypothesis that the slope is shallower for the higher pulse rate. The predicted patterns of the amplitude JNDs for the four experiment conditions **A** to **D**. If pulse rate has no effect on loudness growth or loudness variability, the amplitude JNDs would be equal for all the four conditions. If loudness variability is greater at higher rates, the JND would be larger in condition **C** than **A** and in condition **B** than **D**. If loudness growth is shallower at higher rates, the JND would be larger for condition **D** than **C**.

loudness variances of target and reference stimuli respectively, and δ_C refers to stimulus-independent central noise and uncertainty in loudness judgements. The loudness difference (ΔL) is the JND in loudness between target and reference stimuli, and is larger when the variance of the target or reference stimulus is greater. For simplicity of the schematics in Fig. 2 only, the criterion for 80 % loudness discrimination of target and reference stimuli is achieved when the difference between the means of the two loudness distributions is large enough such that the variance arrows do not overlap. The stimulus-independent central noise is ignored in these schematics because it is expected to similarly affect the four experiment

conditions. Based on the hypothesis that loudness variability is greater for the higher-rate pulse train, ΔL is predicted to be the largest for condition **B** (where both target and reference stimuli are at 3000 pps) and the smallest for condition **A** (where both target and reference are at 500 pps). Equal ΔL is expected for conditions **C** and **D** where one stimulus is at the lower rate and the other at the higher rate. The ΔL for these two conditions is predicted to be between the ΔL of conditions **A** and **B**.

The hypothetical current amplitude JNDs of the target stimuli in the four experiment conditions are shown by the loudness-versus-amplitude plots in the panels a to d of Fig. 2. For each condition, A_{80} is the

target current amplitude at loudness L_{80} (target being perceived just louder than the reference) and A_{50} is the target current amplitude at L_{50} (target being perceived as equally loud as the reference). The current amplitude JND of the target in each condition is shown by ΔA , which is the difference between A_{80} and A_{50} . The current amplitude JND (ΔA) would depend on ΔL (mean loudness difference between target and reference) and the slope of the function that relates target's current amplitude to loudness. The relation between target's current amplitude and loudness is approximated by a line in these schematics (which is plausible given the presumably small range between L_{50} and L_{80}) and the slopes are plotted with the assumption that the growth of loudness with current amplitude is shallower for the higher pulse rate. In the following paragraphs, we describe how the current amplitude JNDs obtained in the four experiment conditions can be used to compare loudness variability, loudness JND, and the growth of loudness with current amplitude associated with the 500- and 3000-pps pulse trains.

Condition A Versus B

Condition A and condition B differ in both reference and target pulse trains. Two factors could contribute to the differences in target current amplitude JNDs between these two conditions: ΔL and loudness growth slope of the target. Hypothetically greater loudness variability for the higher-rate pulse train would result in a larger ΔL in experiment condition B than A and therefore a larger ΔA (see panels a and b of Fig. 2). Hypothetically shallower slope for the higher-rate pulse train would contribute to the larger ΔA in condition B than A. As can be seen from the probability-versus-loudness plots of Fig. 2, the larger ΔL for condition B than A would be related to greater loudness variability of both target and reference pulse trains. The ΔL difference between conditions A and B is expected to be larger than the ΔL difference between condition pairs that differ in target or reference stimulus only. Conditions A and B, for which the rate of the reference stimulus is the same as the rate of the target, are the standard conditions for comparing current amplitude JNDs of pulse trains at different pulse rates (Kreft et al., 2004a; Galvin and Fu, 2009).

Condition A Versus C

The target pulse train (500 pps) is identical between conditions A and C; therefore, the same loudness growth slope describes the relation between ΔA and ΔL in these two conditions (see loudness-versus-amplitude plots of panels a and c of Fig. 2). Thus, a

difference in ΔA between these two conditions would indicate a difference in ΔL only. As demonstrated in the probability-versus-loudness plots of Fig. 2, the ΔL difference between conditions A and C can be explained by the difference in the reference loudness variability between these two conditions. Based on the hypothesis that loudness variability is greater for the higher-rate pulse train (as depicted in the schematic plots of Fig. 2), a larger ΔA would be expected for experiment condition C than A. In other words, the current amplitude JND of the 500-pps target would be larger in the different-rate reference condition (where the rate of the reference is different from the rate of the target). On the other hand, equal current amplitude JNDs for conditions A and C would indicate that the pulse rate of the reference had no effect on its loudness variability.

Condition B Versus D

A similar comparison to above can be applied to the current amplitude JNDs of conditions B and D that have targets at 3000 pps. Since the target is identical for conditions B and D, a difference in current amplitude JND between these two conditions would indicate a difference in ΔL and would be related to the differences in loudness variability associated with the reference pulse trains (see panels b and d of Fig. 2). Assuming greater loudness variability for the higher-rate pulse train, a larger ΔA would be expected for the experiment condition B than D. In other words, current amplitude JND for the 3000-pps target would be larger in the same-rate reference condition (where the rates of the target and reference are the same). This prediction for the 3000-pps target is in the opposite direction to the prediction that was made above for the 500-pps target stimulus (smaller current amplitude JND in the same-rate reference condition).

Condition C Versus D

Current amplitude JND results of conditions C and D can be used to compare loudness growth slopes of the 500- and 3000-pps pulse trains. In these conditions, one of the target or reference stimuli is at the lower rate and the other is at the higher rate, meaning that ΔL (which is proportional to the square root of sum of the variabilities associated with target and reference stimuli) is equal between these two conditions (see probability-versus-loudness plots in panels c and d of Fig. 2). Any difference in ΔA between conditions C and D can only be attributed to the difference in target loudness growth slope between these two conditions (see loudness-versus-current plots in panels c and d of Fig. 2). A hypothetically shallower slope for the higher-rate pulse train would result in a larger ΔA for condition D than C. Equal ΔA for these two

conditions would indicate that loudness growth slope is similar for the two rates.

In summary, the pattern of the current amplitude JNDs obtained in the four experiment conditions can be used to evaluate the hypotheses regarding the effects of pulse rate on loudness variability and the growth of loudness with current amplitude. The predicted current amplitude JND patterns for the four experiment conditions (A to D) are shown in the schematic bar plots in panel e of Fig. 2. If pulse rate has no effect on loudness growth or loudness variability, the current amplitude JNDs would be equal in the four experiment conditions ($A = B = C = D$). If loudness variability is greater for the higher-rate pulse train, the current amplitude JNDs would be different for the same-rate and different-rate reference conditions, and the direction of this difference would depend on the target rate: the JND for the 500-pps target would be larger in the different-rate than the same-rate reference condition ($C > A$), and the JND for the 3000-pps target would be smaller in the different-rate than the same-rate reference condition ($B > D$). If loudness growth is shallower at the higher rate, the current amplitude JND would be larger for the 3000-pps than the 500-pps pulse train in the different-rate reference condition ($D > C$).

Procedures

Current amplitude JNDs for the experiment conditions A to D (shown in panels a to d of Fig. 1, respectively) were obtained using adaptive 2-interval 2-alternative forced choice procedures. Target and reference pulse trains were presented in the two intervals in random order with a 500-ms silent gap in between. The subjects' task was to identify whether the first or the second interval was louder. The stimuli were 300 ms (millisecond) trains of symmetric biphasic square pulses with 25 μ s (microsecond) phase duration and 8 μ s interphase gap. The pulses were presented in monopolar MP1+2 mode on electrode 12 of the 22-electrode array of the subjects' implants. Electrical stimuli were streamed to the subjects' implants using Cochlear Nucleus Implant Communicator (NIC) and L34 research processor provided by Cochlear Corporation. Psychophysical procedures and stimulus presentation were controlled by custom software in MATLAB (MathWorks).

For each experiment condition, the A_{80} target level (with 80 % probability of the target being identified louder than the reference) was obtained using the adaptive "3 down-1 up" procedure. This procedure converges to 79.4 % probability (Levitt, 1971). The A_{50} target level (with 50 % probability of the target being identified louder than the reference) was obtained in two different methods for the same-rate

and different-rate reference conditions. For the same-rate reference conditions A and B (where the rate of the reference was identical to the rate of the target), the A_{50} target level was equal to the level of the reference pulse train. For the different-rate reference conditions C and D (where the rates of target and reference pulse trains were different), the A_{50} target level was estimated from the average of target levels corresponding to approximately 80 and 20 % probability of the target being judged louder than the reference stimulus (A_{80} and A_{20} levels, respectively). The A_{20} level was obtained using the adaptive "1 down-3 up" procedure, which converges to 20.6 % probability (Levitt, 1971). We decided to use the method of averaging A_{20} and A_{80} levels rather than directly estimating the A_{50} level in a "1 down-1 up" procedure. This assured that a fairly accurate estimate of the A_{50} level would be obtained. For each of the four experiment conditions, the current amplitude JND was the difference between the A_{80} and the A_{50} target levels.

The adaptive procedures started by setting the level of the target pulse train such that the target was perceived louder than the reference in the "3 down-1 up" procedures and quieter than the reference in the "1 down-3 up" procedures. The level of the target stimulus adapted by a step size of 4 CL (clinical level) for the first two reversals and 2 CL for a further eight reversals. One CL in Cochlear Freedom implants is equivalent to a 0.157-dB change in current units (microamps). The average of the final six reversals (in CL) of each procedure was set as the procedure result. The results of 6 runs (4 runs in some subjects) of each adaptive procedure type were averaged to set the A_{80} and A_{20} target levels for each experiment condition. The procedures were performed separately and were not interleaved.

The experiment started with conditions A and D, which had the reference stimulus at 500 pps. The level of the 500-pps reference stimulus was initially set at 60 % of the tested electrode's dynamic range (the difference between the most comfortable and threshold levels in CL). This level was rated as "comfortable/soft" by all the subjects. The level of the 3000-pps reference for conditions B and C was set at the A_{50} level of the 3000-pps target obtained in condition D. At this level, the 3000-pps pulse train was equally loud as the 500-pps reference pulse train. Thus, the reference stimuli were equally loud for all the four experiment conditions. Because the reference levels for conditions B and C relied on the A_{50} target level obtained in condition D, the procedures for conditions B and C started after completing the testing for conditions A and D. The adaptive procedures for condition pairs A and D were presented in random order, to reduce learning effects and within-session fatigue effects. Similarly, the adaptive procedures for conditions B and C were presented in

random order. The whole experiment was repeated at a lower level where the level of the 500-pps reference pulse train was set at 40 % dynamic range (DR) corresponding to subjective rating of “soft/very soft” by all the subjects. Note that dynamic range was measured in this study only for setting stimulus levels at 60 and 40 % DR. The experiments required a total of about five 2-h testing sessions including breaks.

The pulse rate of the stimuli that were chosen for this study was within the range that has typically been used in the clinical devices by different CI manufacturers (ranging from 250 up to 5000 pps). The smaller rate (500 pps) was chosen to be above the typical 300-pps limit of temporal pitch perception (Carlyon et al., 2010). The reason for this choice was to reduce as much as possible the likelihood of a strong perceptual difference other than loudness between the two pulse rates, which could make the loudness comparisons difficult in the conditions that had different rates for the target and reference stimuli and could result in boosted current amplitude JNDs (Oxenham and Buus, 2000). We evaluated the discrimination of equally loud pulse trains of 500 and 3000 pps in a second test, in order to assess the extent to which the two pulse trains differed in other perceptual attributes than loudness. Discrimination of equally loud 500- and 3000-pps reference pulse trains (at the louder 60 % dynamic range level) was measured in a 4-interval forced choice procedure. The stimulus in three of the intervals was the 500-pps pulse train. One of the intervals presented in random order was the 3000-pps pulse train. Subjects’ task was to select the different stimulus. Stimulus level in each interval was roved by ± 2 CL to limit discrimination cues provided by small residual loudness differences. Correct percent identification of the different interval in 30 trials was recorded as the discrimination score.

Statistical Analysis

Two-way repeated measures ANOVA was performed using the SigmaPlot scientific data analysis and graphing software (version 12.5). The two within-subject factors were target rate (500 or 3000 pps) and reference rate condition (same-rate or different-rate).

RESULTS

The current amplitude JND results obtained in the four experiment conditions are shown in the bar plots of Fig. 3. The left panel shows average current amplitude JNDs obtained with the louder stimuli at

60 % DR, and the right panel shows the average current amplitude JNDs obtained with the softer stimuli at 40 % DR. Error bars are the across-subject standard errors. The category on the abscissa is the rate of the target pulse train (500 pps in conditions A and C and 3000 pps in conditions B and D). The same-rate reference columns refer to the conditions where the rate of the reference was the same as the rate of the target (conditions A and C). The different-rate reference columns refer to the conditions where the rate of the reference was different from the rate of the target (conditions B and D). The JNDs are shown in both dB and CL (clinical level) units (the dB units were obtained by multiplying the CLs by 0.157).

Louder Stimuli at 60 % DR

The direction of the results obtained with the stimuli at 60 % DR (left panel of Fig. 3) is consistent with greater loudness variability for the higher-rate pulse train (see Fig. 2e). For the 500-pps target, the average current amplitude JND is smaller in the same-rate reference condition (reference at 500 pps) than the different-rate reference condition (reference at 3000 pps). The opposite pattern can be observed for the 3000-pps target, where the current amplitude JND is larger in the same-rate reference condition (reference at 3000 pps) than the different-rate reference condition (reference at 500 pps). These patterns are consistent with the signal detection theory predictions of Fig. 2 when loudness variability is greater for the 3000-pps pulse train than the 500-pps pulse train. The current amplitude JND results were subjected to two-way repeated measures ANOVA with factors target rate (500 or 3000 pps) and reference rate condition (same or different in regard to the target rate). The analysis showed no significant main effect of target rate ($F(1,39) = 3.53$, $p = 0.093$) and no significant main effect of the reference rate condition ($F(1,39) = 0.159$, $p = 0.699$). However, a significant interaction between the two factors was observed ($F(1,39) = 8.22$, $p = 0.019$). A post hoc analysis using the Holm-Sidak method for pairwise comparisons confirmed that the current amplitude JND of the 500-pps target was significantly larger in the different-rate than the same-rate reference condition ($t = 2.181$, $p = 0.045$), and the current amplitude JND of the 3000-pps target was significantly smaller in the different-rate than the same-rate reference condition ($t = 2.618$, $p = 0.019$). The statistical analyses support the hypothesis that loudness variability is greater for the 3000-pps pulse trains than the 500-pps pulse trains.

Loudness growth slope did not seem to be significantly different between the 500- and 3000-pps pulse trains at 60 % DR level. The post-hoc analysis (the Holm-Sidak method) showed no significant difference

Fig. 3. The average current amplitude JND results for the different conditions of target and reference stimuli are shown in both dB and clinical units. The results obtained at the louder and softer stimulus levels are shown in the left and right panels, respectively. Error bars are the across-subject standard errors. The asterisks indicate statistically significant differences

between current amplitude JNDs obtained for the 500- and 3000-pps in the different-rate reference condition ($t = 0.695$, $p = 0.5$). If loudness growth slope was shallower for the higher-rate pulse train, the current amplitude JND would be larger in condition D than C (Fig. 2e). This prediction is not consistent with the results.

The post hoc analysis confirmed that current amplitude JND was larger for the 3000 pps than the 500 pps in the same-rate reference condition ($t = 2.802$, $p = 0.016$). This is consistent with the previous findings that current amplitude JNDs are larger for higher-rate pulse trains (Kreft et al., 2004a; Galvin and Fu, 2009). The two same-rate reference conditions (A and B) differ in both target and reference pulse trains. As described in the “Methods” section and shown in Fig. 2, greater loudness variability of both target and reference stimuli could contribute to the larger loudness JND found in condition B than in condition A. It was predicted that the difference in loudness JND between these two conditions would be larger than the difference in loudness JND between any pair of conditions that differed in reference or target stimulus only (conditions pairs A and C, condition pairs B and D, and condition pairs C and D). The JND results of Fig. 3 are consistent with this prediction. The current amplitude JND difference between the two same-rate reference conditions is approximately 0.16 dB or 1.02 CL. This difference is larger than the JND difference between the same-rate and different-rate reference conditions for both target rates (approximately 0.053 dB or 0.34 CL for the 500-pps target and 0.064 dB or 0.41 CL for the 3000-pps target). It should be noted that the rather small current amplitude JNDs and the small current ampli-

tude JND difference between the two rates may be due to a steep growth of loudness with current amplitude. This does not necessarily mean that loudness JNDs and the loudness JND difference between the two rates were small.

The JND results obtained for the stimuli at 60 % DR are not likely to be strongly influenced by a bias due to a perceptual difference other than loudness (i.e., pitch or timbre) between the 500- and 3000-pps pulse trains. The current amplitude JNDs would be boosted if distinct pitch or timbre percepts for the two pulse trains made loudness comparisons difficult in the different-rate reference conditions (Oxenham and Buus, 2000). Opposite to the direction predicted by such bias, the current amplitude JND of the 3000-pps target was significantly smaller (better) for the different-rate than the same-rate reference condition. The lack of a bias due to a perceptual difference other than loudness between the 500- and 3000-pps pulse trains is in agreement with the results of the rate discrimination test. Equally loud 500- and 3000-pps pulse trains were not easily discriminable by most of the eight tested ears (two subjects were excluded from this test due to time constraints). The percent discrimination of the two pulse trains varied between 25 and 92 % with an average of 58.9 % and standard deviation of 22.94 %. Using a discrimination criterion of 70 %, only three of the eight tested ears could discriminate the two rates (92, 77, and 72 %). The performance of three cases was within the 95 % confidence interval for chance performance (41 %).

The results obtained for the stimuli at 60 % DR were not likely to be influenced by the testing order of experiment conditions. As described in the “Methods” section, the experiment conditions that

had the reference pulse train at 3000 pps (conditions B and C) were tested after completing experiment conditions with the reference pulse train at 500 pps (conditions A and D). However, the current amplitude JND measures were significantly larger (poorer) for condition C than A and for condition B than D. The current amplitude JNDs were poorer for the conditions that were tested later, which rules out a significant effect of procedural learning due to testing order.

Softer Stimuli at 40 % DR

The data with the softer stimuli at 40 % DR were obtained from 9 out of the 10 tested ears; one participant was unable to continue the experiment. Unlike the results obtained with the stimuli at 60 % DR, the pattern of the results at the softer stimuli (right panel of Fig. 3) is not consistent with greater loudness variability for the higher-rate pulse train. The current amplitude JND results were subjected to two-way repeated measures ANOVA with factors target rate (500 or 3000 pps) and reference condition (same-rate or different-rate in regard to the target). The analysis showed a significant main effect of the target rate ($F(1,35) = 11.488$, $p = 0.01$), no significant effect of the reference condition ($F(1,35) = 2.467$, $p = 0.155$), and no significant interaction between the two factors ($F(1,35) = 0.344$, $p = 0.574$). The current amplitude JNDs were significantly larger for the 3000-pps pulse train than the 500-pps pulse train regardless of whether the reference was at the same rate as the target or at a different rate. While these results are not consistent with the predictions of signal detection theory when loudness variability is different for the two pulse trains, they are consistent with a shallower loudness growth slope for the higher-rate pulse train (see Fig. 2e). The current amplitude JND measures were significantly larger for the 3000- than the 500-pps target in the different-rate reference condition.

A perceptual difference other than loudness between the 500- and the 3000-pps pulse trains may have slightly biased the current amplitude JND results with the stimuli at 40 % DR, since the JNDs in the different-rate reference conditions were slightly but not significantly larger than the JNDs in the same-rate reference conditions. But this bias is not likely to have influenced the conclusions. If loudness variability was greater for the 3000-pps pulse train, the current amplitude JND for the 500-pps target would be larger in the different-rate than the same-rate reference condition. A bias due to a strong perceptual difference other than loudness between the two rates would boost the JND of the 500-pps target in the different-rate reference condition and would result in a more significant difference between the different-rate and

same-rate reference conditions. This prediction is not consistent with the observation that the current amplitude JND for the 500-pps target was not significantly different between the same-rate and different-rate reference conditions (right panel of Fig. 3). The observed pattern of JND results for the stimuli at 40 % DR may have been influenced by the testing order of experiment conditions. Learning effect could have resulted in smaller current amplitude JNDs for the conditions that were tested later in the experiment (B and C), and this may have contributed to lack of significant current amplitude JND difference between the same-rate and different-rate reference conditions for the two pulse rates.

The effects of pulse rate on loudness variability and loudness growth slope seem to be dependent on stimulus level. At the louder level tested (60 % DR), there was no significant difference between loudness growth slopes at the two rates. At this level, the difference in the current amplitude JNDs obtained in the same-rate reference conditions A and B could mainly be attributed to the difference in loudness JND (and loudness variability) between the two pulse rates. For the softer stimuli (at 40 % DR), the difference in the current amplitude JNDs obtained in conditions A and B could only be related to loudness growth slope difference between the two pulse rates. It should be noted that this study was designed solely to compare loudness variability and loudness growth for the two pulse rates. The results do not provide any information about the relative contributions of loudness growth and loudness variability to the current amplitude JND measures.

Practical Implication of the Results

The results of this study provide the evidence that loudness variability and loudness JND of CI users can be affected by stimulation pulse rate. In a more practical term, these results provide predictions regarding the effect of pulse rate on intensity resolution (the number of discriminable acoustic intensity steps). For the stimuli at 60 % DR, the current amplitude JND was 0.16 dB (or 1.02 CL) larger at 3000 pps than at 500 pps in the same-rate reference condition. This corresponds to a 60 % JND difference between the two pulse rates (0.27 dB at 500 pps versus 0.43 dB at 3000 pps). As discussed above, the observed current amplitude JND difference is mainly related to greater loudness variability and loudness JND at higher rate (there was no effect of pulse rate on loudness growth slope for the stimuli at 60 % DR). Therefore, assuming that loudness is proportional to current amplitude in dB, the 60 % larger current amplitude JND at the higher pulse rate indicates that loudness JND was 60 % larger at 3000

than at 500 pps. This is equivalent to saying that the number of discriminable loudness steps was 38 % smaller (i.e., divided by 1.6) at 3000 than at 500 pps (across the upper portion of the dynamic range, where an effect of rate on loudness JND was observed). As demonstrated in the Appendix, the number of loudness JND steps is equal to the number of acoustic intensity JND steps (or intensity resolution). Thus, increasing pulse rate from 500 to 3000 pps might reduce the number of discriminable acoustic intensity steps by 38 % (across the upper portion of the dynamic range). This is significant, because a smaller number of acoustic intensity JND steps (poorer intensity resolution) is expected to impair perception of speech features that rely heavily on intensity cues, such as some consonant features (Azadpour and McKay, 2014). Granted, there are caveats to be considered, particularly the fact that the present study did not measure the number of acoustic intensity JNDs at each stimulation rate. However, it is clear that the intensity resolution degradation we observed at higher stimulation rates could potentially have important effects on perception of speech features by CI users, which would be worth further investigation.

DISCUSSION

This study evaluated the effect of pulse rate on loudness discrimination of CI users using an approach based on signal detection theory. Current amplitude JNDs were obtained for target pulse trains of 500 and 3000 pps using reference pulse trains that were either at the same rate as the target or at a different rate. The experiments were performed at two different loudness levels. At the louder level (60 % DR), the current amplitude JND results varied with the reference stimulus, and the direction of JND changes was consistent with greater noise or variability in perceived loudness of the higher-rate pulse train. The results support the hypothesis that pulse rate of cochlear implant stimulation can affect variability in loudness perception and therefore loudness JND. For the softer stimuli (at 40 % DR), the current amplitude JNDs did not vary with reference stimulus. The effect of stimulation rate on loudness JND seems to depend on stimulus level.

The results suggest that high-rate CI stimulation strategies may be detrimental to transmission of envelope cues. Increasing pulse rate from 500 to 3000 pps may cause as much as 38 % reduction in the number of discriminable loudness and intensity steps across the upper half of the dynamic range, which may significantly affect perception of speech cues that

rely on envelope sensitivity. These findings are not consistent with the results of the previous studies that also measured current amplitude JNDs to investigate the effect of stimulation pulse rate on loudness JND (Kreft et al., 2004a; Galvin and Fu, 2009). In those studies, the effects of pulse rate on the growth of loudness with current amplitude was accounted for by normalizing current amplitude JNDs by the dynamic range of the stimuli, with the assumption that loudness growth functions are linear across the whole dynamic range. The effect of pulse rate on current amplitude JNDs somewhat disappeared after normalization, which led to the conclusion that pulse rate does not have a significant effect on loudness JND. This conclusion, however, relies on the validity of the simplifying assumptions that loudness growth functions are linear and that the effects of loudness growth slope can be eliminated after normalizing current amplitude JNDs by the dynamic range. In practice, loudness growth can be heavily non-linear (meaning that the slope considerably varies across the loudness range) and the measure of the dynamic range relies on subjective loudness ratings and may not be accurate. The approach in this study did not require any knowledge about loudness growth functions.

The finding of this study that the noise or variability in loudness percept may be greater at higher pulse rates suggests that increasing pulse rate might significantly impair detection and discrimination of rapid amplitude modulations. According to the temporal integration models of auditory perception, detection of rapid amplitude variations requires the ability to resolve and compare the outputs of short integration windows (Plack et al., 2002; McKay et al., 2013). Greater sensory noise or variability in neural processing may have a greater influence on the output of shorter integration windows. This is because the random-like sensory noise may smear when neural responses are integrated over relatively long temporal windows, similar to the ones that are presumably used for rating overall loudness or detecting slow modulations. Thus, the effect of pulse rate may be more pronounced when rapid amplitude modulations rather than steady current level increments are being discriminated. This is consistent with the findings of previous studies that at higher pulse rates, rapid modulations of current amplitude on a CI electrode require larger modulation depths to be detected (Galvin and Fu, 2005; Pfingst et al., 2007; Fraser and McKay, 2012; Green et al., 2012). Although larger current amplitude modulation depth thresholds at higher pulse rates may be related to shallower loudness growth slopes, which could be compensated by adjusting acoustic-electric mappings in the CI processors and do not necessarily indicate poorer sensitivity to rapid acoustic intensity variations, the

effect of carrier pulse rate was shown to somewhat persist after normalizing modulation depths by the dynamic range (Galvin and Fu, 2009; Fraser and McKay, 2012). The observed evidence that perception of rapid amplitude modulations becomes poorer at higher pulse rates is supported by animal neurophysiological studies, which showed that phase locking of cortical neurons to amplitude modulations deteriorates at higher pulse rates (Middlebrooks, 2008).

The greater variability in perceived loudness of high-level and high-rate pulse trains may be explained by the temporal response properties of auditory nerve fibers. At higher pulse rates, auditory neurons respond less regularly and more stochastically to individual pulses of pulse trains (Zhang et al., 2007; Miller et al., 2008). The stochasticity of neural response patterns at higher pulse rates has been attributed to neural mechanisms such as refractoriness, spike-rate adaptation, accommodation, and facilitation (Boulet et al., 2015). More stochastic and asynchronous neural spikes may contribute to greater variability in total neural spikes within loudness integration windows and thus lead to greater variability in loudness perception. The observed level-dependency of the effect of pulse rate on loudness variability may be explained by the level-dependency of auditory nerve responses. At lower stimulation levels, auditory nerve responses are stochastic and irregular for both low- and high-rate pulse trains (Miller et al., 2008). This can explain the finding that increasing pulse rate did not have a large effect on loudness variability at the softer stimulus level.

The number of discriminable current amplitude steps across the dynamic range of a CI electrode is generally poorer than that for acoustic tones in normal hearing listeners and varies largely across individuals as well as across different electrode contacts within individual (Nelson et al., 1996; Wojtczak et al., 2003). Some CI users have access to only a few discriminable current amplitude steps within the dynamic range of an electrode (Nelson et al., 1996). This is by no means comparable to the number of resolvable levels of acoustic tones available to normal hearing listeners, which is close to a hundred (Schroder et al., 1994). Differences in envelope resolution among CI users and between electric and acoustic hearing could be explained by internal noise or variability in sensory processing and perception. Sensory neural responses may be more variable in CI users compared to normally hearing listeners due to reasons related to deafness, neural degeneration, or the lack of precise neural synchrony mechanisms in electric hearing. Particularly, the lack of neural phase locking may play an important role because acoustic intensity discrimination seems to deteriorate at high frequencies where phase locking

to specific phases of acoustic tones is not expected (Carlyon and Moore, 1984). The difference in sensory noise mechanisms introduced by acoustic and electric hearing remains an important topic for future research.

This study introduced a novel approach for comparing internal noise or variability in loudness perception among different stimuli. There have been previous attempts to quantify absolute amount of internal noise in auditory perception using methods that were developed based on signal detection models (Spiegel and Green, 1981; Jesteadt et al., 2003). These methods, however, rely on specific assumptions about the relation between acoustic intensity and loudness in the normal hearing system and are not easily generalizable to CIs. Assessment and quantification of sensory noise and variability in perception is a challenge for the neuroscience field. In fact, the underlying mechanisms for the noise or variability in neural processing are not clearly understood (Faisal et al., 2008). Some of the existing theories relate sensory or perceptual noise to the noise or randomness in responses of individual and population of neurons, and some others attribute internal noise to deterministic approximations in the complex computations performed by the neural system (Beck et al., 2012). Although this study did not evaluate the mechanisms of internal noise or perceptual variability, the finding that the variability in loudness percept can be affected by pulse rate of cochlear implant stimulation may suggest the hypothesis that noise or variability in loudness perception is significantly contributed by stochasticity of neural responses at the peripheral auditory processing.

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COMPLIANCE WITH ETHICAL STANDARDS

Conflict of Interest The authors declare that they have no conflict of interest.

APPENDIX

The aim of this section is to mathematically demonstrate that the number of acoustic intensity JNDs (or the number

of discriminable intensity steps) available to CI users is equal to the number of JND steps along the perceptual dimension of loudness.

Assume that Ψ is the psychophysical transformation between current amplitude A on a CI electrode and the perceived loudness L , and Φ is the function that maps envelope intensity I of the corresponding acoustic channel to current amplitude A . The perceived loudness of the stimulus is:

$$L = \Psi(A) = \Psi(\Phi(I)) \quad (1)$$

Assume ΔL , ΔA , and I are the just noticeable differences (JND) in loudness, current amplitude, and acoustic intensity respectively. Using Eq. (1), the relation between ΔL , ΔA , and I can be described by:

$$\Delta L = \Psi(A + \Delta A) - \Psi(A) = \Psi(\Phi(I + \Delta I)) - \Psi(\Phi(I))$$

After expanding the terms $\Psi(A + \Delta A)$ and $\Psi(\Phi(I + \Delta I))$, ΔL can be written as:

$$\begin{aligned} \Delta L &= \Psi(A) + \Delta A \frac{d\Psi(A)}{dA} + \text{H.O.T} - \Psi(A) \\ &= \Psi(\Phi(I)) + \Delta I \frac{d\Psi(\Phi(I))}{dI} + \text{H.O.T} - \Psi(\Phi(I)) \end{aligned}$$

ΔL can be rewritten as:

$$\Delta L = \Delta A \frac{dL}{dA} + \text{H.O.T} = \Delta I \frac{dL}{dI} + \text{H.O.T}$$

The H.O.T (higher order terms) can be ignored if ΔA and I are small and the current-to-loudness and intensity-to-current functions are approximately linear within the small range. Therefore:

$$\Delta L = \Delta A \frac{dL}{dA} = \Delta I \frac{dL}{dI} \quad (2)$$

Equation (2) shows that ΔL can be described by ΔA and the slope of the current-to-loudness function ($\frac{dL}{dA}$). ΔL can also be described by I and the slope of the intensity-to-loudness function ($\frac{dL}{dI}$). Equation (2) can be rewritten as:

$$\frac{dL}{\Delta L} = \frac{dA}{\Delta A} = \frac{dI}{\Delta I} \quad (3)$$

The number of loudness JNDs (or the discriminable loudness steps) across the loudness range L_1 and L_2 can be mathematically formulated as (Allen and Neely, 1997):

$$N_L = \int_{L_1}^{L_2} \frac{dL}{\Delta L}$$

Similarly, the number of current amplitude JNDs (or the discriminable current amplitude steps) within the amplitude

range A_1 and A_2 that corresponds to the loudness range L_1 and L_2 can be written as:

$$N_A = \int_{A_1}^{A_2} \frac{dA}{\Delta A}$$

Similar to above, the number of acoustic intensity JNDs (or the discriminable intensity steps) within the intensity range I_1 and I_2 that corresponds to the loudness range L_1 and L_2 can be written as:

$$N_I = \int_{I_1}^{I_2} \frac{dI}{\Delta I}$$

Using Eq. (3) it can be demonstrated that:

$$N_L = N_A = N_I$$

The number of intensity and current amplitude JNDs is equal to the number of loudness JNDs only. The growth of loudness with current amplitude (Ψ), the acoustic-to-electric mapping (Φ), the absolute values of I_1 , I_2 , A_1 , and A_2 and the dynamic ranges $I_2 - I_1$ and $A_2 - A_1$ are irrelevant to the number of discriminable level steps.

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