The effect of stimulation rate on spectral acuity in cochlear implant users

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Abstract

The aim of the current study was to investigate the effects of pulse rate on spectral acuity in cochlear implant patients using a masking paradigm. High rates of electrical simulation may limit speech perception due to channel interactions between electrodes. Spectral acuity was measured with three different stimulation rates using a masking paradigm. The masking stimuli were presented at 300, 900, and 1800 pulses per second (pps/ch) on electrode 12. The probe stimulus was presented on electrodes 11, 12 and 13 at 900 pps/ch. It was hypothesized that the higher stimulation rates would show an increase in masked thresholds. The results of this experiment were that the two higher rates of stimulation have significantly higher masked thresholds than the lowest rate. There was no significant difference between the masked thresholds for the three electrodes measured at each rate. It was concluded that channel interactions occur due to increased rate of stimulation but this may not influence spectral acuity as much as temporal acuity.

1. Introduction

The development of cochlear implants has allowed for the restoration of hearing in patients with profound hearing loss. However, even with modern cochlear implant systems, perception of quiet speech and speech in noise can be difficult or impossible for some listeners. Additionally, the fidelity of cochlear implants is not sufficient for complex acoustic stimuli such as music. One aspect of speech processing that could potentially aid in these areas is manipulating the rate of electrical stimulation. Recent cochlear implant systems make increasingly higher rates of stimulation possible, and the study of high rates of stimulation may be useful in implementing new speech processing strategies. It is also important to further our understanding of any negative consequences of stimulation at high rates.

High rates of stimulation have been predicted to improve speech perception in cochlear implant users by providing more stochastic responses similar to acoustic stimulation (Rubinstein, Wilson, Finley, & Abbas, 1999). Higher rates of stimulation can also increase the users' dynamic range, which was been shown to have positive effects (Zeng *et al.*, 2002). However, several studies investigating the effects of pulse rate on speech perception have proven inconclusive. One study using the Nucleus® 22 cochlear implant found that there was significantly worse speech perception at 100 pps/ch but no difference in speech perception between 150 to 500 pps/ch (Fu & Shannon, 2000). Several studies using the Nucleus® 24 electrode implants have found contradictory results. When comparing 250, 807, and 1615 pps/ch with different signal to noise rations (SNR), there was no difference between 250 and 807 pps/ch for any SNR. The 1615 pps/ch condition was significantly worse at the middle and low SNR tested (Vandali, Whitford, Plant, & Clarke, 2000). Another study examined 720 and 1800 pps/ch with speech perception at different sound levels in quiet. In this study the 1800 pps/ch condition demonstrated significantly better speech recognition scores at the lowest sound level of 50dB. However, this may have been due to the overall greater amount of stimulation due to higher pulse rates. Finally, a study comparing a range of pulse rates between 250 pps/ch and 2400 pps/ch, with different numbers of active electrodes, found no differences due to the pulse rate used (Friesen, Shannon, & Cruz, 2005). Overall, there is little evidence to support improvements to speech perception at high pulse rates using the Nucleus® implant.

When using electrical stimulation at higher pulse rates there are the potential problems of increased adaptation and channel interactions in the auditory system. Stimulating at higher pulse rates requires pulses to be presented at shorter time intervals. This can potentially lead to increased adaptation in the peripheral and central components of the auditory system. Furthermore, electrical stimulation of the cochlea can lead to channel interactions between the different stimulating electrodes. Evidence from gap detection, modulation detection and forward masking studies suggest that stimulation on one electrode may influence the responses of a wide portion of the electrode array (Chatterjee, 1999; Chatterjee & Oba, 2004; Chatterjee & Shannon, 1998; Hanekom & Shannon, 1998). Higher rates of stimulation can lead to an increase in the total amount of charge presented to the electrode array and this in turn may lead to an increase in channel interactions.

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Forward masking has been successfully used to investigate channel interactions in cochlear implant users and has been shown to occur over a similar time-course in both normal hearing and cochlear implant listeners (Chatterjee & Oba, 2004; Shannon, 1990). Forward masking refers to the phenomenon whereby a shorter stimulus has an increased detection threshold when following a longer supra-threshold stimulus. In forward masking experiments the longer supra-threshold stimulus is referred to as the mask or masker, and the shorter stimulus is referred to as the probe. The time course of masking in cochlear implant users suggests that there will be an increase in the probe threshold when it follows a masker by 100ms and greater depending on the listener (Nelson & Donaldson, 2002). When a masker and probe are presented on different electrodes, the changes in probe masked threshold can be used as a measure of channel interactions.

The present study aimed to investigate the effects of forward masking at different stimulation rates. This was done to asses the channel interactions that may occur at different rates of stimulation. It was hypothesized that higher rates of stimulation would lead to more interactions between electrodes and therefore there would demonstrate greater masked thresholds at higher rates. Furthermore, it was hypothesized that higher rates of stimulation would interact with electrode separation, indicating a decrease in spectral acuity due to higher rates.

2. Method

2.1. Participants

A total of seven participants with past experience participating in research experiments were recruited from a pool of research volunteers. All participants used the Nucleus CI24R or Nucleus® CI24M cochlear implant and had at least one year of experience with their device. Participants were offered reimbursement for their travel expenses to and from each research session. Participants' ages ranged from 54 to 84 years (mean = 69, standard deviation = 13). Details of each participant's etiology of deafness, implant device and years implanted are presented in Table 1. Also note that participants were not selected based on speech perception scores, as the experimental procedure did not explicitly require speech recognition or production. This study was approved by the Royal Victorian Eye and Ear Hospital, Human Research Ethics Committee (Approval Number 97/318H/02).

Table 1: Participant information.

Participant	Age	Years Implanted	Etiology of deafness	Cochlear implant
1	84	6	Otosclerosis	CI24M
2	74	3	Unknown	CI24R
3	54	11	Unknown	CI24M
4	72	8	Unknown	CI24M
5	84	8	Unknown	CI24M
6	59	4	Unknown	CI24R
7	55	1	Unknown	CI24R

2.2. Materials

Masking stimuli were presented using a SPrint speech processor controlled by an IBM compatible computer. A custom program running in MATLAB was used to run the three interval forced choice adaptive task. A color touch-screen monitor was used to present visual cues corresponding to the stimulus intervals and to record the participant's response during the experiment. A second color monitor was used by the experimenter to observe the trials progress.

The stimuli to establish T-levels, C-levels and loudness balancing were presented using a SPEAR3 processor connected to an IBM compatible computer running SeedSpeak Software[1].

2.3. Stimuli

All electrical stimuli were charge balanced biphasic pulses in the monopolar configuration of the Nucleus® implant. The masking stimulus was always presented on electrode 12 of the implant array with a duration of 300ms at 25 µs/phase. The masking stimulus was presented at 300, 900, or 1800 pps/ch. Threshold levels, comfort levels and loudness balancing were conducted with stimulus parameters identical to the masking stimuli, and the closest possible pulse rate to the masking stimuli within the limitations of the SeedSpeak software.

The probe stimulus was presented on three electrodes of the implant array. The probe was presented on electrodes 11, 12 and 13. The probe stimulus was always presented as a 900 pps/ch pulse train of 30ms duration at 25 µs/phase. When determining threshold and comfort levels the SeedSpeak software was not capable of providing a 30ms pulse train, and therefore the closest possible duration of 100ms was used to represent the probe stimulus.

The delay between the end of the masker and onset of the probe was set at 30ms in all masking trials.

2.4. Procedure

Threshold, comfort levels and loudness balancing were conducted during one session. Once comfort levels had been determined this information was entered into the custom three interval forced choice (3IFC) software allowing for threshold levels to be found using the 3IFC adaptive method. The following sessions consisted of completing a number of masking trials for each of the different test stimuli. The final test session was used as a contingency session to complete any missing trials and to confirm threshold levels using the 3IFC method.

2.4.1. Threshold and comfort levels

Threshold and comfort levels were determined by an Audiologist using the standard clinical methods. Threshold and comfort levels were determined for both the probe stimuli and for the masking stimuli. Threshold levels were found by choosing a moderate current level and stepping the current down until the participant indicated they could no longer hear the stimulus. At this point the Audiologist would raise and lower the current level in small steps to verify this current level was at threshold.

Comfort levels were found by slowly raising the current level from a moderate level until the participant indicated it was becoming uncomfortable. The Audiologist would then verify this current level with the participant and step the

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current level up or down in small steps based on the participants responses. Once the participant indicated they were comfortable with the current level that value was recorded as the comfort level.

2.4.2. Loudness balancing

Loudness balancing was conducted once threshold and comfort levels had been established. Loudness balancing was performed between the three pulse rates used for the masking stimuli. Loudness balancing was conducted using the SeedSpeak software by presenting the three stimuli in succession at 90% of the participant's dynamic range. The participant was asked to determine if the loudness was the same for each of the three stimuli. If a particular stimulus was perceived to be different in loudness the current level of that stimulus was raised or lowered accordingly. This procedure was repeated several times with the stimuli presented in different sequences to verify perception at the same loudness.

2.4.3. Three interval forced choice task

Once threshold and comfort levels had been determined using the standard clinical methods, it was possible to safely use the custom three interval forced choice (3IFC) software to find threshold levels and masked thresholds. Comfort levels for each participant were entered into the 3IFC software for the three electrodes presenting the probe. The program terminated the trial and presented a warning if the adaptive algorithm attempted to raise the current level over the comfort level.

The 3IFC tasks made use of the QUEST adaptive algorithm to determine the 63% correct response of the threshold, representing d' = 1. The QUEST adaptive algorithm calculates the certainty of response based on the standard deviation of the previous responses (Watson & Pelli, 1983). This information can then be used to lower or raise the probe stimulus level in the next trial. The QUEST adaptive procedure also steps the test stimulus in smaller intervals based on the certainty of previous responses.

The intervals in the 3IFC program were graphically represented as three equally-spaced grey selection buttons on a plain grey background. The 3IFC software presented the three stimuli separated by 500ms gaps. When each stimulus interval was presented the corresponding button would turn green. The participants were required to choose which of the three intervals they believed contained the target stimuli. Once they had selected their answer the program highlighted the correct response interval in blue and provided a button to move on the next presentation.

At the beginning of every trial the first three stimuli were not used in calculating the threshold level. These stimuli were presented to allow the participant a chance to detect the stimuli without causing large deviations in the calculations needed for efficient use of the adaptive algorithm. Once the completion criterion was met the trial ended and the participant was presented with a screen indicating that testing had been completed.

2.4.4. 3IFC threshold levels

To determine threshold levels the desired electrode was selected and the masking stimuli current was set to zero. This allowed the same 3IFC software to be used to determine both the threshold levels and masked thresholds. Thresholds were determined in a random order. In the threshold task the probe stimulus was randomly presented in one of the three intervals, while the other two intervals were silent. Participants were instructed to listen for which of the three intervals they thought contained a sound and to make their best guess if uncertain. Each trial continued until the QUEST algorithm reached a standard deviation of at most 0.8 current levels for the threshold or the trial reached 50 presentations.

2.4.5. 3IFC masked thresholds

Masked thresholds were determined for each of the possible combinations of pulse rate, probe electrode and time interval. Trials were grouped by the three pulse rates 300, 900 and 1800 pps/ch. The order of presentation for each pulse rate was assigned to participants using a pseudo-Latin square design. The probe electrode and time interval order were randomly presented within each pulse rate block.

The masking stimuli were set at 90% dynamic range based on the values found through the standard clinical procedure for threshold and comfort levels. These values were loudness balanced between each of the three pulse rates. Once the current level was set, the masking stimulus was played during each of the three intervals in the 3IFC task. The probe stimulus was randomly presented during one of the three intervals. Participants were instructed to listen to all three intervals and to determine which interval did not sound the same as the others. This generic instruction was given because not all probes induced the sensation of two separate sounds, but still produced a perceptible difference. Each trial continued until the QUEST algorithm reached a standard deviation of at most 0.8 current level for the masked threshold or the trial reached 50 presentations.

2.4.6. Normalization of masked thresholds

Masked thresholds and absolute thresholds were obtained for each probe electrode from every participant. Although it would be possible to compare the masked thresholds and the absolute threshold of the probe directly, it would not take into account differences in dynamic range between participants. To account for different dynamic ranges on each electrode between each participant a normalized value of masked threshold was calculated. The normalized value was calculated by determining the difference between masked threshold and absolute threshold and dividing this value by the participant's dynamic range for that electrode. Therefore the masked threshold was represented as a percentage of the probe dynamic range and not as the raw current level for all analyses.

3. Results

The data for the normalized threshold was analyzed using a factorial analysis of variance (ANOVA). The fixed factors used were pulse rate and electrode. Participants were represented as a random factor.

There was a significant main effect for pulse rate, (F = 15.21, p <0.01). However, there was no significant main effects for electrode, (F = 0.35, p > 0.05). There was also no significant interaction between the pulse rate and the electrode, (F = 1.14, p > 0.05).

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The three pulse rates tested were displayed by electrode as can be seen in Figure 1. The two higher rates have a higher masked threshold on all three electrodes than the lower rate. This was tested using a post-hoc Tukey's HSD between pulse rates. This analysis found that there was no significant difference between the two higher rates and a significant difference between each higher rate and the lower rate.

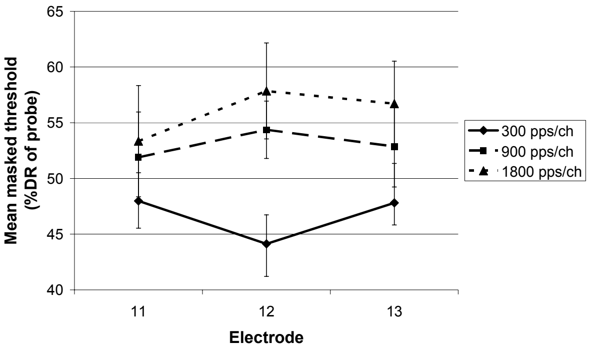

Figure 1: Mean masked threshold over each electrode.

4. Discussion

The results of this study have shown that there is a significant difference in forward masking due to increased rates of electrical stimulation with cochlear implants. The two higher rates of stimulation, 900 and 1800 pps/ch, demonstrated higher masked thresholds than the 300 pps/ch. Therefore hypothesis that higher rates of stimulation would lead to an increase in masked thresholds was supported.

However, the hypothesis that pulse rate would interact with electrode spacing was not supported. The interaction between pulse rate and electrode was expected to be significant, representing a greater spread of masking at higher rates. The results did not show a significant interaction effect between pulse rate and electrode, or a significant difference between the three electrodes. This suggests that although higher rates did lead to increased masked thresholds, this increase was uniform across the three electrodes tested in this experiment. Therefore, it is likely that there is no decrease in spectral acuity due to higher rates of stimulation but rather a general increase in masked threshold due to increased pulse rate.

The results suggest that increasing the rate of electrical stimulation on one electrode will lead to an interaction with neighboring electrodes. When the masking electrode was set to electrode 12, the probe thresholds on electrodes 11 and 13 were well above the absolute threshold of the probe. This result is expected and consistent with past studies using multiple electrode forward masking (Chatterjee & Oba, 2004; Throckmorton & Collins, 1999). Additionally, the presence of masking at a 30ms separation between masker and probe is consistent with past cochlear implant forward masking studies.

The presence of increased forward masking due to higher rates of stimulation also provides support for past findings. When using animal models, increased rates of electrical stimulation in the cochlea have lead to greater degrees of adaptation (Haenggeli, Zhang, Vischer, Pelizzone, & Rouiller, 1998). Although the relationship between forward masking and adaptation is not completely understood, psychophysical forward masking has similar response characteristics to physiological measurements (Brown, Abbas, & Gantz, 1990).

Spectral acuity was expected to be influenced by the rate of electrical stimulation but this was not observed. Past studies have indicated that forward masking may be better correlated with temporal acuity than with spectral acuity (Throckmorton & Collins, 1999). It may be that forward masking was not the most appropriate measure of spectral acuity and that another measure such as electrode discrimination would have been preferable. It is also possible that high rates have a greater influence on temporal acuity than on spectral acuity. The results of this study suggest that higher rates can influence channel interactions and adaptation. Therefore, these processes may interfere more with the fine temporal detail than with general acuity between electrodes.

The results may provide a potential explanation for the lack of conclusive evidence for increased speech perception at higher pulse rates. Higher pulse rates were originally expected to provide more stochastic responses and more temporal detail. However, any increase in temporal detail provided may not be perceptible due to the effects of channel interactions and adaptation. The present study has shown that higher rates of stimulation can lead to an increase in channel interactions and adaptation. Therefore, it is possible that any benefits of higher stimulation rates are counteracted by increased channel interactions.

Further studies are still needed to confirm the specific effects of stimulation rate on speech perception. It would be beneficial to directly compare masked thresholds at different stimulation rates and speech perception at these rates. In speech perception, consonants are generally thought to correspond better with temporal acuity and vowels with spectral acuity. One method of testing the effects of pulse rate on spectral and temporal acuity would be to compare consonant and vowel recognition scores at different pulse rates.

5. Conclusions

In conclusion, higher rates of electrical stimulation did not have a significant interaction with electrode spacing. However, higher rates of stimulation did have a significant effect on masked thresholds. Therefore, high rates of stimulation may influence temporal acuity more than spectral acuity in cochlear implant users.

6. Notes

[1] The SPEAR3 processor and research system was developed by the Cooperative Research Centre for Cochlear Implant and Hearing Aid Innovation. A product brief, "SPEAR3 Product Brief – 3rd Generation Speech Processor for Electrical and Acoustic Research", can be obtained from HearWorks, 384 Albert Street, East Melbourne, 3002, Australia, or online from http://www.hearworks.com.au

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8. References

Brown, C. J., Abbas, P. J., & Gantz, B. (1990). Electrically evoked whole-nerve action-potentials - data from human cochlear implant users. *Journal of the Acoustical Society of America, 88*(3), 1385-1391.

Chatterjee, M. (1999). Temporal mechanisms underlying recovery from forward masking in multielectrode-implant listeners. *Journal of the Acoustical Society of America, 105*(3), 1853-1863.

Chatterjee, M., & Oba, S. I. (2004). Across- and within-channel envelope interactions in cochlear implant listeners. *Jaro-Journal of the Association for Research in Otolaryngology, 5*(4), 360-375.

Chatterjee, M., & Shannon, R. V. (1998). Forward masked excitation patterns in multielectrode electrical stimulation. *Journal of the Acoustical Society of America, 103*(5), 2565-2572.

Friesen, L. M., Shannon, R. V., & Cruz, R. J. (2005). Effects of stimulation rate on speech recognition with cochlear implants. *Audiology and Neuro-Otology, 10*(3), 169-184.

Fu, Q. J., & Shannon, R. V. (2000). Effect of stimulation rate on phoneme recognition by nucleus-22 cochlear implant listeners. *Journal of the Acoustical Society of America, 107*(1), 589-597.

Haenggeli, A., Zhang, J. S., Vischer, M. W., Pelizzone, M., & Rouiller, E. M. (1998). Electrically evoked compound action potential (ecap) of the cochlear nerve in response to pulsatile electrical stimulation of the cochlea in the rat: Effects of stimulation at high rates. *Audiology, 37*(6), 353-371.

Hanekom, J. J., & Shannon, R. V. (1998). Gap detection as a measure of electrode interaction in cochlear implants. *Journal of the Acoustical Society of America, 104*(4), 2372-2384.

Nelson, D. A., & Donaldson, G. S. (2002). Psychophysical recovery from pulse-train forward masking in electric hearing. *Journal of the Acoustical Society of America, 112*(6), 2932-2947.

Rubinstein, J. T., Wilson, B. S., Finley, C. C., & Abbas, P. J. (1999). Pseudospontaneous activity: Stochastic independence of auditory nerve fibers with electrical stimulation. *Hearing Research, 127*(1-2), 108-118.

Shannon, R. V. (1990). Forward masking in patients with cochlear implants. *Journal of the Acoustical Society of America, 88*(2), 741-744.

Throckmorton, C. S., & Collins, L. M. (1999). Investigation of the effects of temporal and spatial interactions on speech-recognition skills in cochlear implant subjects. *Journal of the Acoustical Society of America, 105*(2), 861-873.

Vandali, A. E., Whitford, L. A., Plant, K. L., & Clarke, G. M. (2000). Speech perception as a function of electrical stimulation rate: Using the nucleus 24 cochlear implant system. *Ear and Hearing, 21*(6), 608-624.

Watson, A. B., & Pelli, D. G. (1983). Quest - a bayesian adaptive psychometric method. *Perception & Psychophysics, 33*(2), 113-120.

Zeng, F. G., Grant, G., Niparko, J., Galvin, J., Shannon, R., Opie, J., & Segel, P. (2002). Speech dynamic range and its effect on cochlear implant performance. *Journal Of The Acoustical Society Of America, 111*(1), 377-386.

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