

Selective attentional processes in cochlear implant recipients: measurements of the attentional filter.

Christofer Bester¹, Dona M. P. Jayakody², Geoffrey Hammond³, Donald Robertson¹

¹School of Anatomy Physiology and Human Biology, The University of Western Australia, Crawley, Western Australia, Australia 6009

²Ear Sciences Institute Australia' 1 Salvado Rd, Subiaco, Western Australia, Australia 6008

³School of Psychology, The University of Western Australia, Crawley, Western Australia, Australia 6009

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*Corresponding author: Christo W. Bester. Department of Otolaryngology, Level 2, Peter Howson Wing, Royal Victorian Eye and Ear Hospital

32 Gisborne Street, East Melbourne

Victoria, 3002

AUSTRALIA

christofer.bester@gmail.com

Abstract

In normal hearing subjects, detection of near-threshold tones in noise is influenced by signal certainty. Thus, tones that are presented more frequently than others, and/or are preceded by a clearly audible cue tone of the same frequency (target tones) are detected better than other tones (probe tones). This auditory attentional filter was examined in six cochlear implant (CI) recipients, using acoustic stimuli and direct programmed electrode stimulation. Three of the subjects showed no evidence of an attentional filter. Three subjects showed a relatively higher detection rate of the target frequency or electrode stimulated during the attentional task and in two of these subjects the target benefit was influenced by stimulus certainty. The absence of an attentional filter in some CI recipients is consistent with suggestions that the attentional filter may be generated by efferent modulation of outer hair cells, which would presumably be absent in CI recipients, however the presence of some frequency-selective attentional effects and a near-normal attentional filter in two CI subjects imply that central processes can modulate signal detection in CI recipients according to stimulus certainty. Such central processes might serve as a neural substrate to improve signal detection in CI recipients.

I. INTRODUCTION

It has been long established that the detection of near-threshold auditory signals in background noise is influenced by procedures that affect signal certainty. One example is the so-called “attentional filter” (Greenberg and Larkin, 1968) in which target tones that are presented more frequently than other tones, and/or are preceded by a clearly audible cue tone of the same frequency, are detected at a relatively higher rate than other tones (probe tones) that are presented less frequently, or without a preceding matching cue tone. The role of the attentional filter in detection of more complex signals such as speech is not clear. However, such cue-driven attentional processes could potentially aid in the detection of repeated or expected signals in the presence of background noise. There is evidence that cued detection could play a role in auditory scene analysis and that listeners can use acoustic cues to dynamically track a particular speaker in the presence of competing voices (Wolmetz and Elhilali, 2016, Woods and McDermott, 2015).

It is not known whether cochlear implant (CI) recipients have normal attentional filters. This is of interest, first because of the possible implications of auditory cuing for processing of signals in noise by CI recipients and second, because such knowledge may help to unravel mechanisms underlying the attentional filter. Attentional processes are generally attributed to higher

order central mechanisms, but some evidence suggests that the auditory attentional filter may involve a peripheral action of the medial olivocochlear efferent system (MOCS) which originates in the brainstem and is driven by auditory input (Lieberman and Brown, 1986, Robertson, 2009, Robertson and Gummer, 1985). When activated, the MOCS has been shown to modulate outer hair cell gain in restricted cochlear domains and to thereby cause a release of auditory neural responses from masking by background noise (Lieberman and Guinan, 1998, Lilaonitkul and Guinan, 2012, Robertson, 2009, Kawase et al., 1993, Winslow and Sachs, 1987). Significantly, in patients whose MOCS projection to the cochlea has been interrupted by vestibular neurectomy, the attentional filter is either partially or completely lost, while other measures of peripheral auditory function are unaffected (Scharf et al., 1997, Scharf et al., 1994).

However, psychophysical evidence for MOCS involvement in attentional control of signal detection and in speech-in-noise processing, is contradictory (Giraud et al., 1997, Kumar and Vanaja, 2004, Wagner et al., 2008, de Boer et al., 2012, Walsh et al., 2015, de Boer and Thornton, 2008). CI recipients, with severe to profound hearing loss have absent cochlear outer hair cells over most or all of the normal frequency range. Because the outer hair cells are the principal target of MOCS innervation (Guinan, 2006, Robertson, 1984, Lieberman and Brown, 1986), CI recipients represent a group of subjects who presumably have no possible MOCS action on the cochlea. If the MOCS modulation of outer

hair cells is the mechanism underlying the attentional filter, CI recipients would be expected to show no evidence of an attentional filter with stimuli delivered directly to their surviving auditory nerve fibers. Any evidence that CI recipients can generate an attentional filter would require that in those individuals, there must be central mechanisms that are able to perform this function.

II. METHODS

Subjects

Seven postlingually deafened CI recipients, with hearing loss of various durations and aetiologies, participated in the study (Table 1). All CI subjects used a Cochlear CP810 speech processor and had at least one year's experience with their current processor. The three different electrode types used all consisted of a 24-electrode array, and in all subjects the electrodes were fully inserted. All participants had bilateral severe to profound hearing loss prior to implantation (greater than 70 dB HL with air conduction from 500Hz- 8kHz and no evidence of conductive loss). All but two participants had pre-operative unaided scores of 0% for recognition of simple words (AB word list) presented at 110 dB SPL. These participants would not be expected to have significant remaining inner or outer hair cell activity (Hamernik et al., 1989, Stebbins et al., 1979). Two subjects had some residual unaided hearing assessed using the

AB word list at 110 dB SPL (CI#2 at 29% and CI#4 at 50%). These latter two subjects would be expected to have no functional outer hair cells, but at least some intact inner hair cells. Post implantation scores for CUNY sentences ranged from 90 to 100% across all CI subjects. Five of the subjects were implanted bilaterally, however all measurements in the present work were done monaurally, using the ear with the greatest dynamic range at implant electrode 11. Dynamic range was determined by subtracting the comfort (C) level from the threshold level (T). Participant CI#1 attended only a short preliminary study and withdrew for personal reasons and the mean age of the remaining 6 subjects was 56.2yrs. Cognitive ability was assessed using the standard MoCA score (Dupuis et al., 2015) and ranged from 22 to 30 (Table 1)

Table 1 here

Three additional participants, 1 male and 2 female, ranging in age from 22 to 25 years of age with normal hearing (< 20 dB HL from 250 Hz to 8 kHz, as tested with a Clinical Audiometer) served to test the suitability of one of the experimental protocols.

General procedures

All experiments were conducted in a sound-attenuating room. The overall timing of stimulus delivery in all experiments was controlled by a suite of custom LabVIEW programs run on a Windows PC with output via a soundcard (ASUS Xonar STX). The PC was located outside the sound-attenuating room. All measurements of detection of stimuli were performed using a basic two-interval forced-choice design (2IFC), in which the test signal was presented randomly in one of two observation intervals. On each trial, subjects indicated whether they thought the stimulus was in the first or second interval by pressing the left or right button on the computer mouse. Failure to detect the stimuli resulted in a 50% (chance level) of successful choice of interval measured over a large number of trials. All experiments consisted of initial threshold estimations, then a training session to familiarize the subjects with the nature of the specific attentional task, and the final measurements carried out over a number of repeated sessions. The training session took place over an hour and used the same parameters as the final measurements. Variations in the details of stimulus presentation in the two experiments are described separately below.

Experiment 1- Acoustic presentation

In this experiment, CI recipients listened to free-field sound stimuli. The same standard Cochlear CP810 speech processor was used for all participants with each participant's most recent personal MAP uploaded prior to the experiment. A significant issue was the possible confounding influence of sophisticated on-

board processing executed by the speech processor. To minimize this, the processor was customized to only receive AUX input, and the Adaptive Dynamic Range Optimization and AutoSensitivity Control were disabled. The AUX input was from a Cochlear Lapel Microphone (Z208299), which was fixed in place 1m in front of a GENELEC 8020A loudspeaker. The participants' hearing aids or CIs contralateral to the test ear were switched off for the duration of the experiments.

The 60 dB SPL(A) background broadband noise was generated with a separate Windows laptop computer using SoundForge XP v4.5. It was calibrated with a Bruel and Kjaer Type 2260 Sound Level Meter and a Type 4189 free-field microphone in place of the lapel microphone. The noise spectrum was flat to within +/-1dB from 800Hz to 3.5kHz. The pure tone test signals were 300 ms in length and their frequencies were set at the central frequency of electrodes on the speech processor according to the default Frequency Allocation Table used by all participants. The target frequency was 1.938 kHz, which was chosen because it was the central frequency of electrode 11. The probes were separated from the target and each other by one electrode, on electrodes 15, 13, 9, and 7, which equated to tones of 1.125, 1.438, 2.5 and 3.313 kHz.

Simulation

Prior to any human measurements, a simulation study was conducted to measure the output of the speech processor in response to the noise and pure

tones. An important consideration was whether it was appropriate to include cue tones in the cochlear implant experiments. If the cue tone resulted in an activation of multiple channels that were adjacent to the target channel, this could result in a spread of the cue effect that might attenuate any attentional filter or broaden and make it less evident. The pattern of activation that was generated in response to a pure tone presented at the target frequency and in background noise was measured by attaching a Cochlear CP810 speech processor (with the same settings used in the subsequent experiments) to a custom device (Decoder Implant Emulation Tool (DIET)) which measured the level and rate of stimulation delivered by the speech processor to each electrode. Current level units had a range of 1 to 255, coding for stimulation amplitude over a logarithmic range from 10 μ A to 1.75 mA. Representative stimuli were generated by mixing background noise files produced by SoundForge XP, with test signal tone files produced by the LabVIEW program. The temporal structure of the stimulus is show in Figure 1.

Figure 1 near here.

To simplify analysis, the speech processor used a MAP with a 100 current level dynamic range, using a threshold level (T level) and comfort level (C level) of 100 and 200 current levels respectively, across the electrode array. To simulate the settings of a typical cochlear implant recipient, the CP810 speech processor

used for the simulations was set to a maximum input level (C-SPL) of 75 dB, and in the simulation the pure tone was presented at an amplitude previously measured to produce a 79% detection rate in a normally hearing participant (see below for threshold estimation procedure). The simulations were run with this pure tone at -5 dB, +5 dB, +10 dB and +15 dB relative to this threshold. The five amplitudes of the pure tone were presented to the simulation hardware twice, and the results were averaged. The DIET device produced a database file with the exact current level presented to each electrode on every stimulation cycle.

Figure 2 shows typical results of the simulation performed using the “Implant in a box”. For a threshold level of the tone (centred on electrode 11) there was a discrete increase in the number of stimuli on that electrode, without an obvious increase on adjacent electrodes. However, when the tone intensity was increased above this level, there was an evident spread of the excitation to the more apical adjacent electrode. This software-based spread of excitation could influence the measurements of the attentional filter and for this reason, in all experiments using acoustic stimuli it was decided not to use a clearly audible cue tone. In order to establish conditions appropriate for generating an attentional filter, the target uncertainty was reduced solely using a higher probability of presentation of near-threshold target than near-threshold probe tones.

Figure 2. near here

Threshold estimation & attentional filter procedures

At the start of each session, thresholds were measured for all pure tone frequencies in the presence of continuous background noise using a three-down one-up adaptive staircase with a 2IFC procedure that produced a threshold corresponding to a 79% detection rate (Levitt, 1971). The order in which thresholds were estimated for the different frequencies was randomized between sessions. Every subject reached a lower asymptote during the training session for the threshold task, indicating that thresholds were able to be estimated in a manner comparable to normal hearing subjects. Stimuli were presented in one of two 300-ms observation intervals separated by 300 ms. The two intervals were indicated by a “1” and “2” displayed on the computer monitor. Subjects were prompted to respond 300 ms after the completion of the second interval and the next trial began 1 s after the response. Each trial began with a 600-ms period of noise before the first interval. The tone amplitude decreased in 5-dB steps until the first incorrect response and then changed by 1-dB steps. Eighty trials were presented for each threshold estimate and the mean of the last eight reversals was taken as the threshold, using only the 1dB steps.

The probe-target procedure used the same 2IFC structure. Each run of the experiment contained 192 trials, repeated 3 times in each session, with a 5-minute break between each run. Target and probe frequencies were set at their individual 79% detection thresholds previously determined in the same session. Two of the CI subjects (CI#1 and CI#2) participated in preliminary experiments to test the feasibility of the procedures. Subsequent measurements (6 subjects excluding CI#1) were performed in 5 separate sessions held on separate days. The first session consisted of training runs of the threshold estimation and probe-target procedure. The second session consisted of the target-probe task in which all stimuli were set at their estimated 79% detection thresholds but were all presented with equal likelihood of occurrence. This session was included as a control as it was not expected to generate any attentional filter. The final 3 sessions were devoted to the target-probe task, this time with the 1938Hz target presented on 75% of trials and the remaining 25% of trials distributed equally between the 1125, 1438, 2500 and 3313Hz probes. The order of presentation of the target and probes was randomized at the beginning of each session in blocks of 32 (24 targets and 2 of each probe). The attentional filter was measured over four one-hour long experimental sessions. The first session contained 3 practice runs each of the threshold and probe-target procedures. Subsequent sessions, which were held at least one hour but not more than one week apart, began with threshold estimation, and then 3 runs of the probe-target procedure. The probe-target procedure is based on

those previously reported in the literature (Botte et al., 1997, Dai et al., 1991, Schlauch and Hafter, 1991, Tan et al., 2008).

It is important to note that in all the attentional filter measurements using acoustic stimuli and speech processor, no explicit cue tone was used. This was because the results of the simulation (see Figure 2 above) indicated that the louder cue tone caused a spread of stimulation from the target electrode to at least one of the adjacent electrodes. In the acoustic experiments therefore, expectancy of the target frequency was induced solely by presenting that frequency more often than the probe frequencies.

The 3 normal-hearing participants followed all the above procedures, with the exception that monaural presentation was via headphones (Sennheiser HD-280 PRO), rather than the free field loudspeaker. The headphones were calibrated using a Bruel and Kjaer Type 2260 sound level meter combined with a Bruel and Kjaer Artificial Ear Type 4152 and the background noise spectrum was flat within +/-1dB from 800Hz to 3.5kHz.

Experiment 2–Programmed direct stimulation

Four of the 6 subjects in experiment 1 also performed these experiments, in which no acoustic stimuli were used. Instead, stimulus frames were constructed using the Python programming language (van Rossum, 2007) and presented to the implant electrode array using the Cochlear™ Nucleus Implant Communicator (NIC) software and a Cochlear™ L34 body-worn research

processor connected to the PC via the Cochlear™ POD. The use of stimuli programmed directly to the implant electrodes meant that the problem of software-based spread between channels that was identified in the previous simulation using acoustic stimuli and speech processor was eliminated. For this reason, in the target-probe task, an explicit cue signal matching the target was also programmed into the pattern of stimuli delivered to the electrode array in addition to a higher probability of occurrence of target stimuli employed in the previous experiment. The method of direct programmed stimulation also ensured that any remaining potential confounding factors that might have been introduced by the speech processor in the previous experiment were eliminated.

The construction of the stimuli followed the ACE processing strategy used day-to-day by the CI recipients (Patrick et al., 2006). According to this strategy the Cochlear™ implants used by the participants stimulate on one electrode at a time, with a biphasic pulse (25 μ s pulse width and 8 μ s interphase gap). A 900-Hz rate per electrode, the default setting, was used by all participants in the present experiment. The ACE processing strategy stimulates on 8 corresponding electrodes in a sequential, ascending pattern. These 8 electrode cycles must contain 8 non-repeated electrodes.

All stimuli were programmed in real time, however hardware memory limitations restricted the length of the stimuli to 2.7 seconds. This prevented the use of a continuous background noise as used in the previous experiments.

Instead, the stimuli were constructed to be equivalent to a 2.7-second noise stimulus, with a 300-ms cue stimulus beginning 500 ms after the beginning of the noise, and a 300-ms test signals in one of two intervals, beginning either 300 or 600 ms after the end of the cue stimulus.

The noise was programmed by stimulating randomly selected electrodes throughout the noise period. To follow the ACE processing strategy, the noise was programmed by stimulating 8 randomly selected electrodes during each cycle, from electrodes 3 to 19. An initial current level at an equivalent of 25% of each electrode's dynamic range was used, with an additional jitter of plus or minus up to 3 current levels using a Gaussian distribution. To insert a cue, target, or probe stimulus, a stimulation of the desired electrode was substituted into the existing noise array on the 8-electrode cycles. To do this, one of the electrodes that had been chosen to present noise on one cycle was randomly chosen to be substituted with stimulation on the desired cue, target, or probe electrode. This was done for each cycle over the desired length of stimulation.

Before measuring thresholds and the attentional filter, the background noise was calibrated to produce equal loudness from the low to the high frequency electrodes. Participants were given controls in a graphical user interface to increase or decrease the amplitude of the stimulus and to replay it. They were then presented with a 1s noise stimulus with the amplitude on each electrode set at 25% of each electrode's dynamic range, the range of amplitudes between

the lowest detectable stimulus and the highest stimulus that does not cause physical discomfort. Participants were asked to make the stimulus of comparable loudness to a comfortably spoken conversation. Once this level was reached, the low to high frequency balance of the noise was adjusted. Using the same graphical user interface, the participants were able to increase or decrease the amplitude of the “Low” (electrodes 12, 13, 14, 15, 16, 17, 18, and 19) or the “High” (electrodes 4, 5, 6, 7, 8, 9, 10 and 11) frequencies. The participants were asked to equalize any low or high frequency imbalances, so that the noise sounded equally loud across the electrode array. Any response changed the amplitude in current level increments equal to 5% of the dynamic range on each electrode, and the participants were free to make as many changes as they wished. In practice, none of the participants altered the balance of the noise after setting it to a comfortable loudness. The noise was described by the participants as a “Hiss”, “Fuzz”, or a “TV set to the wrong channel”.

Threshold and attentional filter measurements

The threshold measuring procedure followed the same basic adaptive and 2IFC structure as used in Experiment 1. The initial decrease in stimulus amplitude was 5 current levels until the first incorrect response, after which steps of 1 current level were used. Thresholds were measured at the beginning of each session for the target electrode 11 and each of the probe electrodes, with the

order randomized on each session. All thresholds were measured in the presence of the previously adjusted background noise stimulation.

The attentional filter measurement procedure used the same target-probe structure described for Experiment 1, except for the use of 2.7s long bursts of noise stimuli, rather than a continuous background noise and an explicit cue on the target electrode. The cue stimulus, timed as described above, was presented at +5 current levels relative to the threshold on the target electrode 11, which made it clearly audible. The subjects, all of whom had participated in the previous acoustic experiment reported that they were comfortable performing this modified task. Limitations on subject availability meant that unlike Experiment 1, this second experiment did not incorporate an equal likelihood target-probe condition.

A second programmed direct stimulation experiment was conducted using the attentional filter measurement procedure described above, but the cue and target were shifted to electrode 14. Electrode 14 was chosen as it was outside the electrode range used in the previous attentional filter measurement task (electrodes 9 to 13). Therefore, the detectability of the new target electrode 14 was unlikely to have been affected by prior experience. The probe electrodes were 12, 13, 15 and 16. Only two of the subjects were able to participate in this shifted target experiment.

III. RESULTS

Experiment 1- Acoustic presentation

As explained above, because of limitations imposed on the experimental design by the use of CIs and speech processor, we did not use an explicit cue preceding the target tone, relying instead on the 75% probability of presentation of the target frequency to generate a filter (this is the design originally reported by Greenberg and Larkin (1968)). In addition, we only employed monaural sounds and it was therefore deemed prudent to verify that in our hands, this overall design could indeed generate an attentional filter in normal subjects. Fig 3 shows the averaged results obtained from the three normal-hearing subjects. In the attentional filter task, the detection of the target frequency was close to the 79% detection rate obtained from the prior threshold measurements, whereas the detection rate for the probes was significantly lower and in some cases, was near to 50%. Further confirmation that this benefit in detection of the target was a result of signal certainty was obtained by presenting all stimuli with equal likelihood. In this case, there was no difference between the detection rates of any frequency, a result that was expected because in this case, there was no information present in the equal likelihood condition that could influence signal certainty. These results therefore confirm that the form of stimulus presentation used (monaural, 75% target presentation and no explicit cue) does generate an attentional filter in normal hearing subjects.

Figure 3. near here

Identical experiments were performed on the 6 CI subjects who participated in the full series of experimental sessions. There was considerable variation between subjects in the results obtained, and hence individual data are shown in Figure 4.

Figure 4. near here

CI#4 was the only subject who showed unambiguous evidence for the presence of a genuine attentional filter with characteristics similar to those of normal subjects. In this subject, the target frequency was detected at a higher rate than three of the probes and this “target advantage” disappeared when all stimuli were presented with equal likelihood. In the remaining subjects, evidence for an attentional filter was either absent, partial, or inconsistent. In subjects CI#6 and CI#7 no evidence in support of a filter was found. In these two subjects, there were no significant differences between the detection of any of the probes compared to the target tone either when the target was presented 75% of the time, or when all frequencies were presented with equal likelihood. In subject CI#5, one low and one high frequency probe were detected less than the target and this difference disappeared when all stimuli were presented with equal likelihood. This constitutes some evidence for the

existence of an attentional effect based on signal certainty and favoring target detection relative to those particular probe frequencies. Oddly however, in this subject, the highest frequency probe appeared to be detected better than the 1.938 kHz frequency in both the target-probe and equal likelihood conditions. In CI#3 only the lowest frequency probe was detected significantly less than the target and although in the equal likelihood condition this frequency was no longer significantly different in its detection rate from the target, there was no apparent shift in the actual detection rate as was seen in CI#5. Hence the lower detection of the low frequency probe in this subject did not appear to be a genuine effect of the relative probability of presentation. Subject CI#2 showed what appeared to be a well-behaved attentional filter with the detection rate of all probes being significantly lower than that of the target, but the result for the equal likelihood probe-target presentation was unexpected, as the detection of the lowest and the two higher frequency probes remained significantly lower than for the 1.938kHz tone (the target tone in the 75% target probability condition). This result suggests that in this subject, there was some bias favoring detection of the 1.938 kHz tone relative to the some of the probes during the attentional task, but this bias was not affected by target expectation *per se*.

Experiment 2-Programmed direct stimulation

Four of the previous subjects participated in this experiment in which the speech processor was bypassed and programmed direct stimulation was used to

deliver the probes and target. As in the previous experiment using acoustic stimuli, the level of probes and target was set by using the threshold tracking method to estimate the stimulation level required for 79% detection in the presence of the same background noise used in the attentional filter task. As explained in the Methods, during the attentional task itself, an explicit cue was delivered to the target electrode on every trial, and targets were presented on 75% of the trials.

Results for the four individual subjects are shown in Figure 5. There were some similarities and differences between the results obtained and those of the previous acoustic task in these same subjects.

Figure 5 near here

The one subject who showed clear evidence of an attentional filter in the previous acoustic experiment, (CI#4) showed a similar result in this case, with the lowest and highest frequency probes detected significantly less frequently than the target. CI#2 performed in a manner strikingly similar to during the acoustic stimulus task, in that all probes were detected significantly less successfully than the target. In this case however, the difference was mainly the result of a dramatic increase in the detection of the target rather than a drop in detection of the probes CI#3 showed no evidence of any attentional effects, with all stimuli detected near the expected 79% level. In CI#5, the attentional task resulted in a fall in the detection rate of the target and both

low frequency probes while the highest frequency probe was detected close to the 79% threshold level and as a result its detection rate was significantly higher than for the target. The attentional task using direct stimulation, because it required subjects to listen for probes and targets within noise bursts, rather than continuous background noise as in the acoustic task, was particularly demanding on subjects and for this reason the equal likelihood condition could not be investigated. Figure 6 presents a comparison between the results of experiments 1 and 2 for the four subjects

Figure 6. Near here

In two subjects the programmed direct stimulation was altered so that the target stimulus was delivered to electrode 14 instead of electrode 11. Electrode 14 had not been used for any of the previous direct stimulation. The purpose of this experiment was to test whether an electrode was able to function as a target if it had not been used as the target during the training procedure or main experiment. Figure 7 shows that in both subjects, at least one probe was detected less frequently than the new target electrode. CI#4 provided the best evidence for the expected systematic shift in the filter characteristics. In this subject, stimuli delivered to two probe electrodes were detected less frequently than the new target and one of these was a new probe electrode (electrode 15) and the other was a previous probe (electrode 12).

Figure 7. near here

IV. DISCUSSION

There are few previous studies that directly address the question of selective auditory attentional process in adult cochlear implant recipients. Harris and Kamke (2014) report that adolescent implant recipients show normal cortical evoked potential responses to oddball stimuli when attention was switched from a visual to an auditory task. Other studies have shown that some, but not all, implant recipients, using their speech processors, can segregate auditory streams on the basis of electrode location and other stimulus parameters (Chatterjee et al., 2006, Cooper and Roberts, 2007, Cooper and Roberts, 2009, Harris and Kamke, 2014). In normal hearing subjects, comparisons of mismatch negativity and cognitive components of cortical potentials show that pre-attentive processes can provide a basis for discriminating between different auditory streams that differ in spectral content (Nie et al., 2014). These authors speculate that CI recipients, in whom spectral information may be degraded, might have to rely on more active attentional processes, assumed to be cortical. None of these previous reports investigated the specific phenomenon of the attentional filter that is the subject of the present paper, nor do they consider the possibility that a loss of peripheral mechanisms such

as the MOCS could play a role in determining whether CI recipients can develop an attentional filter.

In this study, the existence of the attentional filter was investigated using two methods of delivering target and probe stimuli. In the first, acoustic free field stimulation and a microphone input to the subjects' speech processor was used. We used the same speech processor for all subjects. A simulation of the speech processor output to the electrode array was used to check for possible software-based spread of excitation between the channels on which the different tones were represented. The results of this simulation indicated that for acoustic stimulation, all target and probe stimuli had to be restricted to threshold levels to avoid spread of excitation, and for this reason, a more clearly audible cue tone was not used. This stimulus regime (75% probability of target tone presentation) was shown to be capable of generating an attentional filter in 3 normal subjects. The small size of the control group meant that it could not be age-matched to the CI group. However, it has been shown that the attentional filter characteristics in adults are not age-dependent (Ison et al., 2002) and hence the differences seen between the CI and normal hearing group, or between the different CI subjects, are unlikely to reflect a general decline in ability to perform the task. (Ison et al., 2002). In this respect it is worth noting that although the subject with the most robust evidence for an attentional filter (CI#4) was 36yrs old (mean age of the CI group 56.2yrs), CI#5, who was 68 yrs old also showed evidence of a partial filter and the youngest CI subject

(CI#3) showed no evidence of a filter. Two of the CI subjects had MoCA scores suggestive of mild cognitive impairment, but this should be treated with some caution, as it has been shown (Dupuis et al., 2015) that hearing impairment can have a significant impact on MoCA scores.

Each subject's thresholds for all stimuli were measured in each testing session and the existence of an attentional effect was inferred when the detection rates changed in a frequency-selective manner during the attentional filter task. An important issue however, was whether or not the sophisticated speech processor software influenced the results obtained, even though all those speech processor functions that were accessible were disabled. For this reason, 4 of the group of 6 subjects used for the acoustic stimulation version of the task we also investigated using direct programmed stimulation which bypassed the speech processor. The overall result was similar in both situations i.e. some subjects showed consistent differences between target and probe detection rate in the attentional task, whereas others did not.

Some of the results obtained are difficult to explain simply in terms of a classical attentional filter. In one CI subject (CI#2) there were differences between the detection of targets and probes during the attentional task that could not be attributed to the expectation of target versus probe stimuli, since using acoustical presentation, the target was consistently detected with greater success than the probes even when all stimuli were presented with equal likelihood. This result suggests that some aspect of the sensation

generated by the target made it more salient than the probe stimuli during the task itself when the subject had to listen across a range of frequencies. The result obtained in CI#5 may be another example of this phenomenon, since during both the acoustical and direct programmed versions of the task, the highest frequency probe was, surprisingly, detected more readily than the target.

It cannot be deduced from these data why some subjects show varying forms of attentional effects and others do not. Differences in aetiology of deafness, implant history and implant performance may all be important (Table 1). It is notable that the one subject who showed all the requirements of a true attentional filter (CI#4) had the best AB word list score (50% correct at 110dB SPL) prior to implantation of their device. It is possible that even the limited input that the auditory pathway received prior to implantation was in some way instrumental in this subject developing or maintaining inherent central mechanisms responsible for generating the filter. However, the other subject with a non-zero pre-implantation word score (CI#2), although they showed a preference for detection of the target tone or electrode, did not satisfy the requirement of a true attentional filter, since this target preference was apparently independent of signal certainty. Furthermore, CI#5, who showed evidence of a partial attentional filter, had no residual hearing prior to implantation.

The results have implications for the possible mechanism of the attentional filter. Brainstem reflex mechanisms that influence hair cell function in specific cochlear regions via efferent outflow, specifically the medial olivocochlear system (MOCS) have been suggested (Scharf et al., 1997) and these mechanisms could not be functional in the severe-profoundly deaf cochlear implant recipients. Some CI subjects did indeed show a complete absence of the attentional filter but contrary to the hypothesis, other subjects showed varying degrees of ability to generate an attentional filter, implying that CI recipients can utilize central processes to achieve better detection of expected targets. In line with this observation, some of the vestibular neurectomy subjects of Scharf et al, still showed some attentional filter, despite an absence of MOCS reflexes. It is notable that in several of the CI subjects that did show attentional effects, the target advantage (difference between target and probe detection) was comparable to that in normal hearing subjects. Although this is limited data, it suggests either that the mechanism of the attentional filter is the same in normal hearing subjects and in CI recipients. An alternative mechanism not requiring MOCS involvement, could involve the establishing of a central template, either by expectation on the basis of more frequent presentation, or by an explicit cue. Signals that matched the template (targets) would be more readily detected than ones that did not (probes) (Wright, 2005).

The results may also be relevant for real world signal processing by CI recipients. The effect of the attentional filter in normal hearing subjects has

been estimated to be equivalent to 3-7dB improvement in signal intensity for expected, or cued sounds. Typical psychometric functions show that an increase in signal intensity of approximately 10dB can change signal detection from chance levels to 100% (Tan et al., 2008) and hence cue-related effects could substantially improve signal detection in the presence of background noise. It is yet to be established what role these processes may play in determining auditory processing in real world listening situations, but if they could be harnessed in CI recipients they have the potential for improving implant performance, especially in noisy environments. It would be of interest to know whether those CI recipients with strong cue-related effects perform better at speech-in-noise processing and whether in subjects with weak or absent effects, some form of targeted auditory training could improve performance.

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ID	Age (yrs)	Sex	Aetiology	Duration of severe to profound unaided HL (yrs)	Implant type	Duration with current CI (yrs)	M
CI#1	40	M	SO	1	CI 512	3	
CI#2	68	M	NI+SO	1	CI 422(SRA)	1	
CI#3	33	F	SO	0.5	CI 24RE (CA)	1.5	
CI#4	36	M	PO+SO	1	CI 422 (SRA)	1	
CI#5	68	F	PO	4-5	CI 512	2	
CI#6	66	M	NI+SO	4	CI 512	2	
CI#7	66	F	PO	14	CI 512	2	

Table I: Characteristics of CI subjects and summary of experimental outcome.

Aetiologies; SO sudden onset, NI noise induced, PO progressive adult onset.

MoCA score (Montreal cognitive assessment).

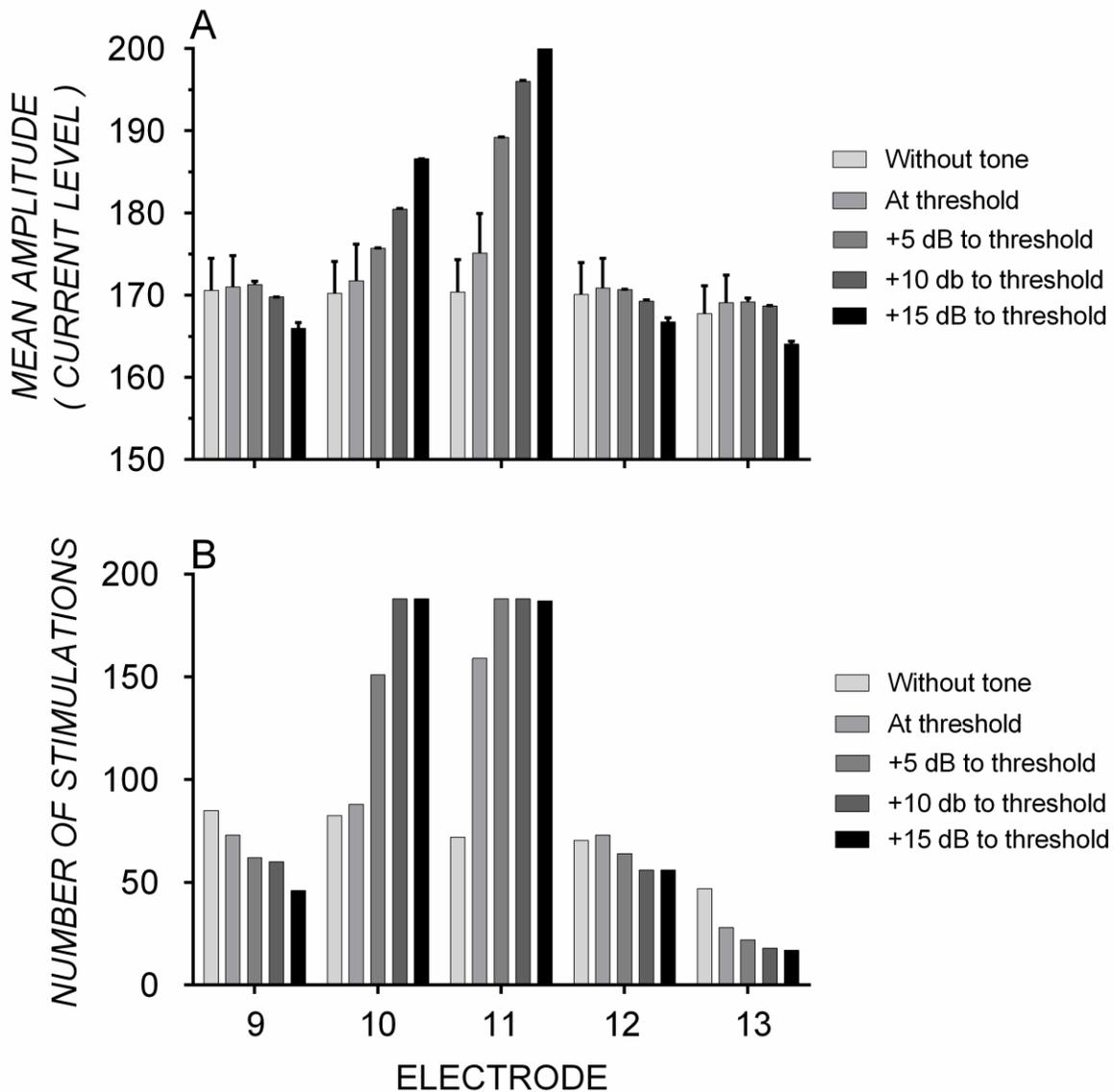


Figure 2. Results of the simulation using tones in noise and an “implant in a box”. The 1.938kHz target tone was used and was presented at various levels in the presence of 60dB SL noise (see Figure 1). Threshold level of the tone was determined as described in Methods. Note increased current amplitude (A) and

higher shock number (B) on electrode 10 as well as electrode 11 as tone intensity is increased above threshold.

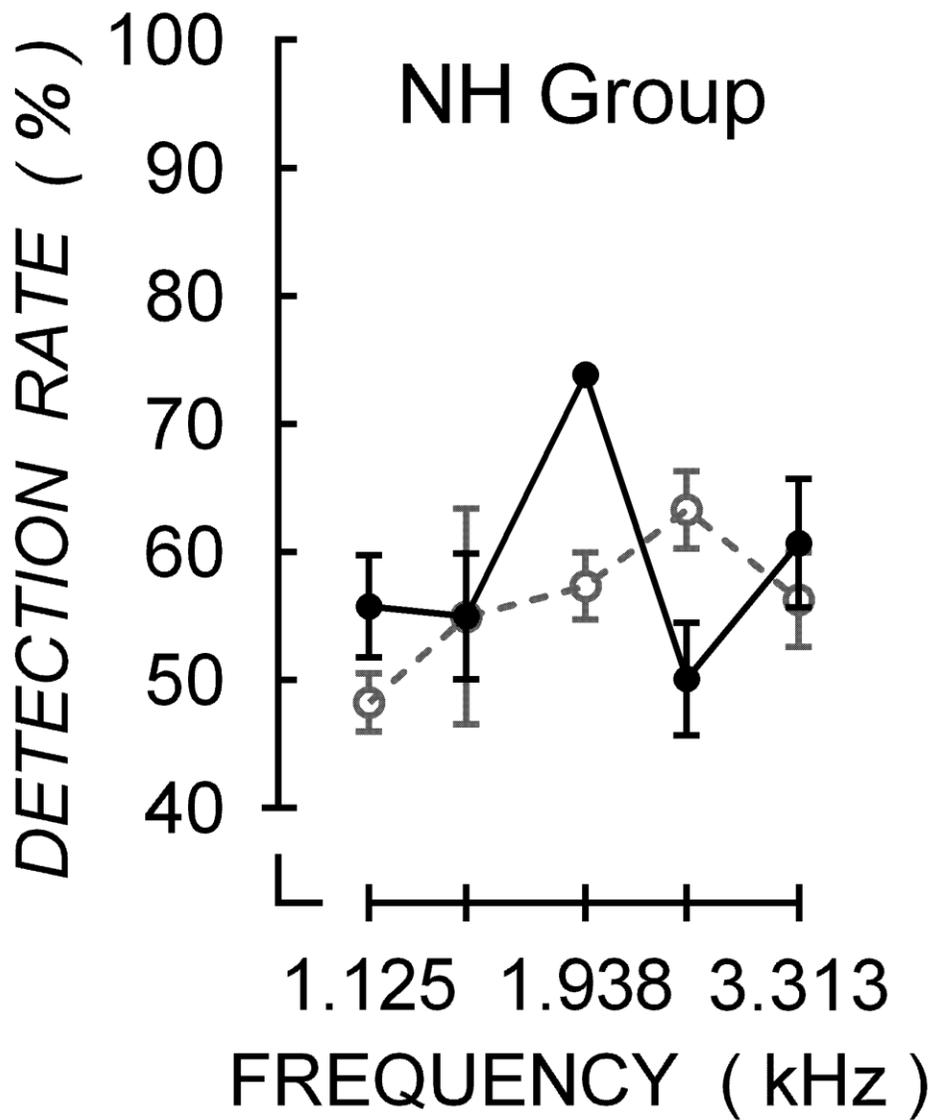


Figure 3. Average results using acoustic stimulation in normal hearing subjects (n=3). Solid lines and symbols, target-probe task with 75% target presentation and remaining 25% distributed equally across the four probes. Target frequency

1.938kHz. Dotted lines and open symbols, all frequencies presented with equal likelihood. Error bars +/- 1 SEM (not shown if SEM <1%).

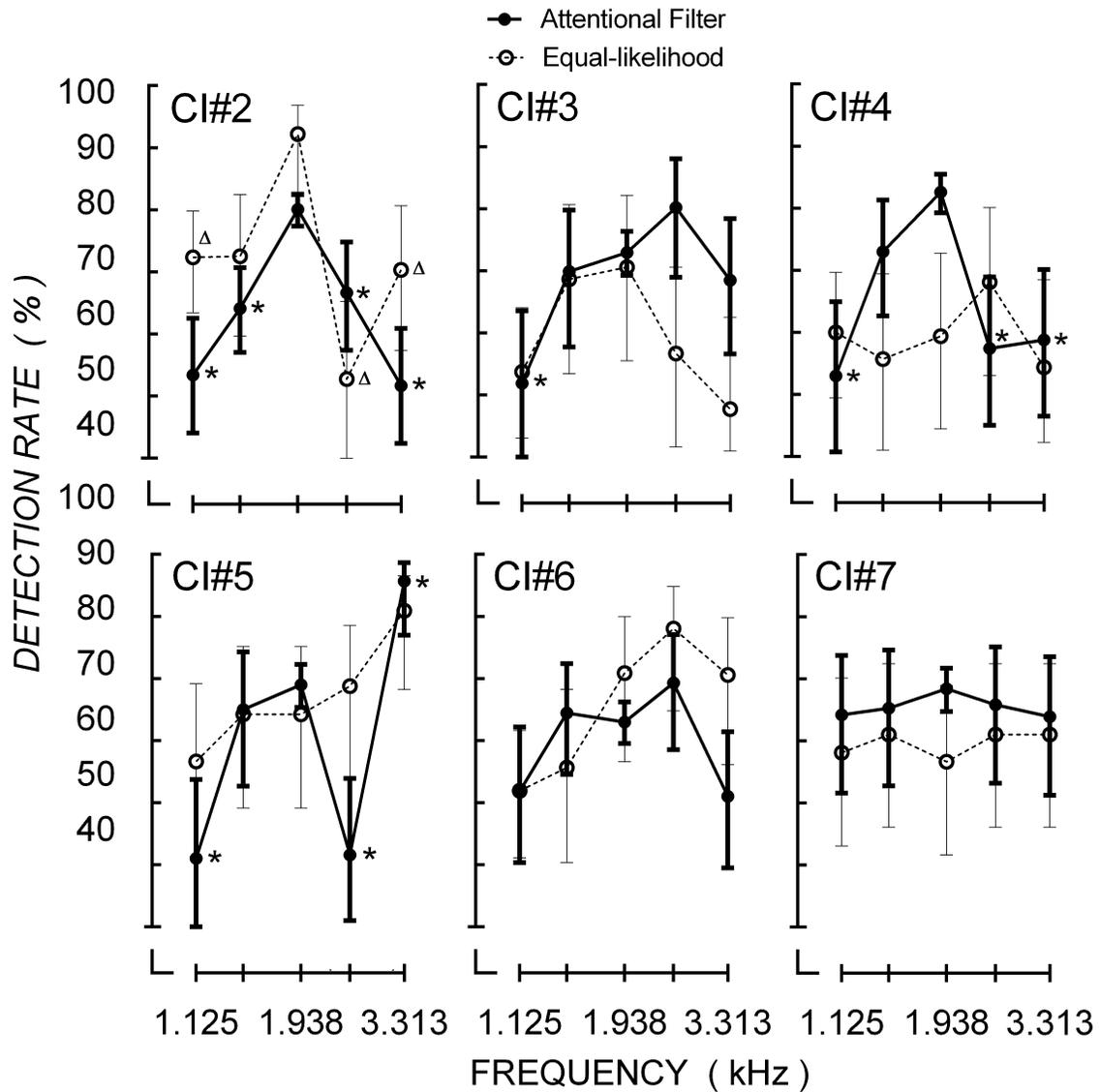


Figure 4. Individual attentional filter results in Experiment 1 for 6 CI recipients. Symbols as in Figure 3. Error bars are 99% confidence intervals. Asterisks and open triangles denote frequencies for which the 99% confidence intervals did not overlap those of the 1.938kHz tone target (asterisks for attentional filter

task and triangle for equal-likelihood task). Note that only in CI#2 are there any substantial differences between 1.938kHz and other frequencies in the equal likelihood condition.

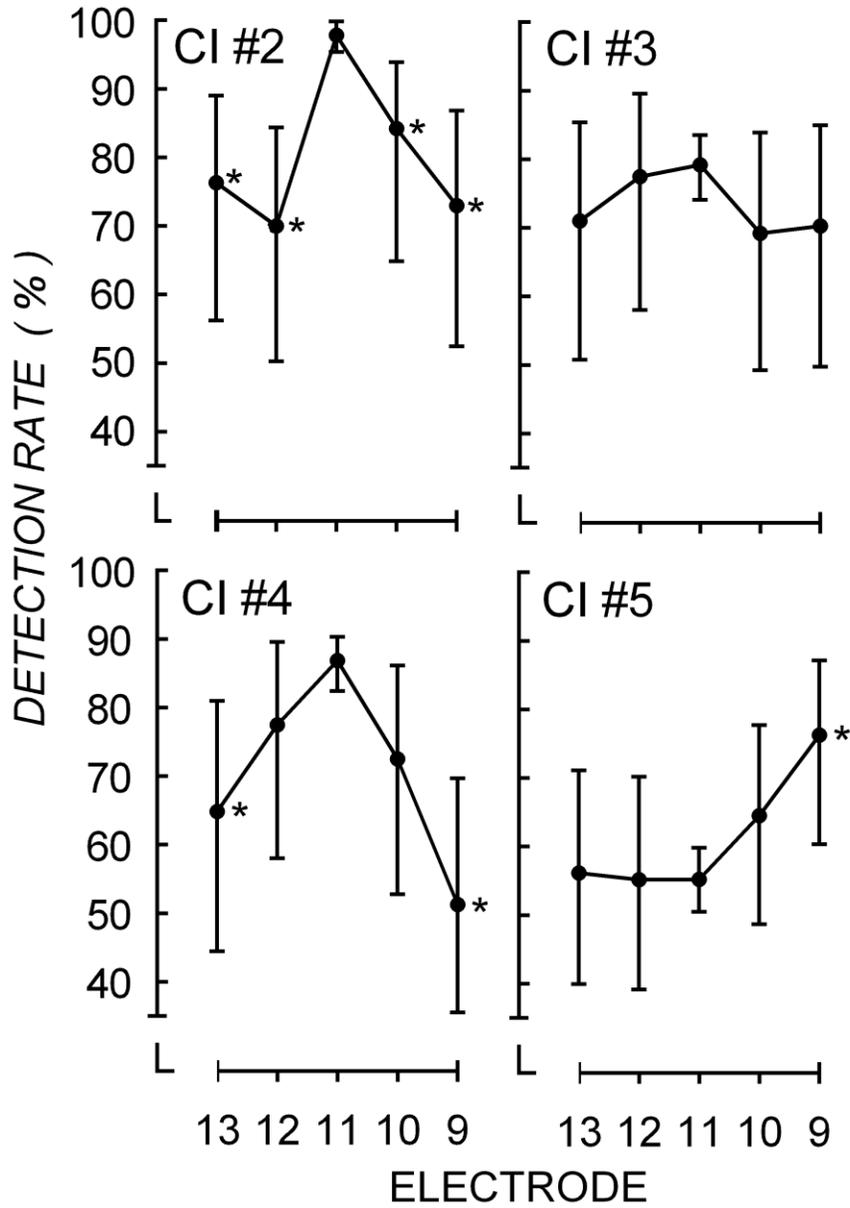


Figure 5. Results of the target-probe task for 4 CI recipients when direct programmed stimuli were used in place of acoustic stimuli, bypassing the subjects' speech processor. All symbols as in Figure 4. Only the target-probe task was performed in this set of experiments.

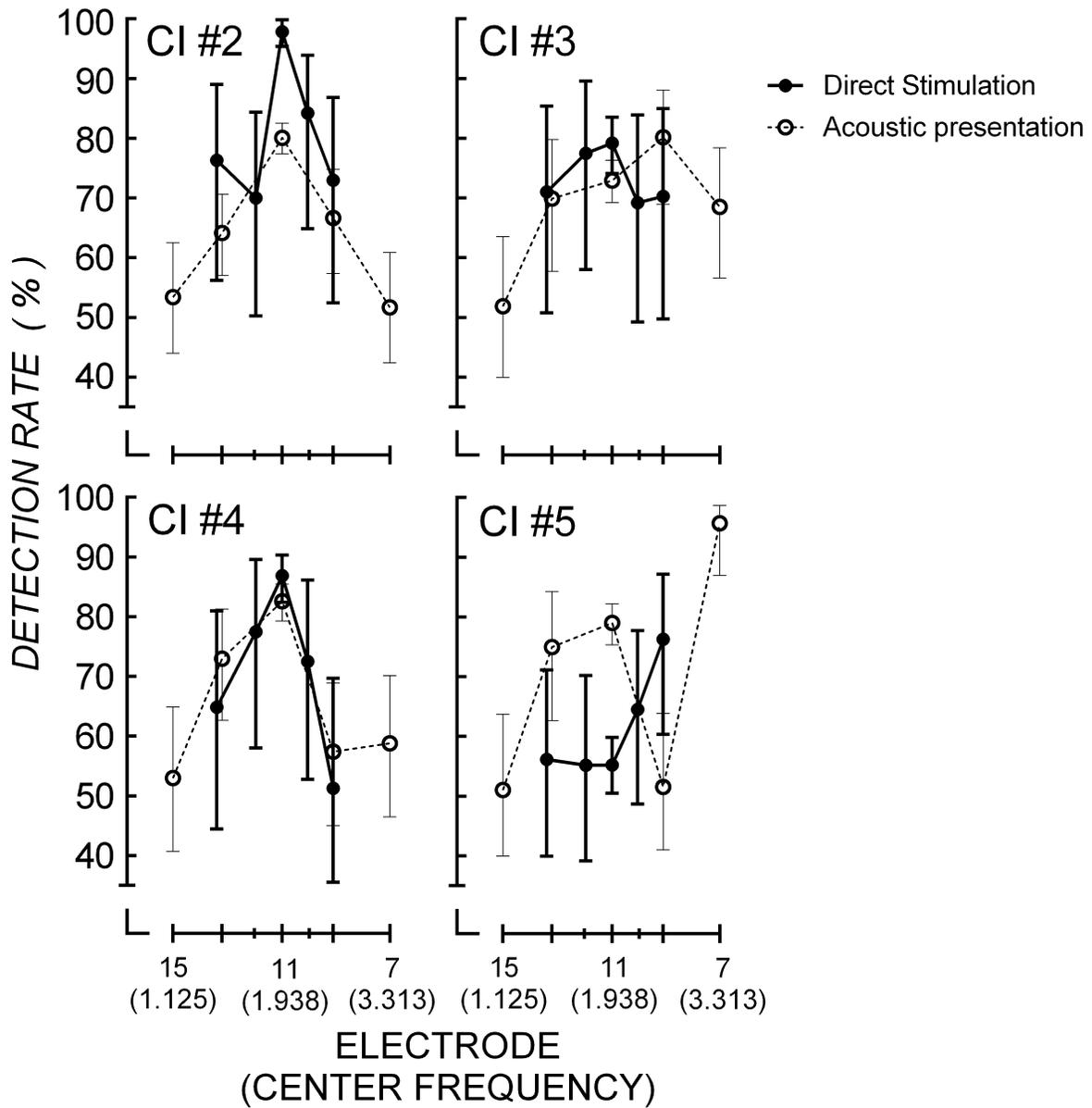


Figure 6. Comparison of results of the target-probe task for the four CI recipients who performed both experiments using acoustic stimuli (dotted lines) and direct programmed stimulation (solid lines). Error bars denote 99% confidence intervals.

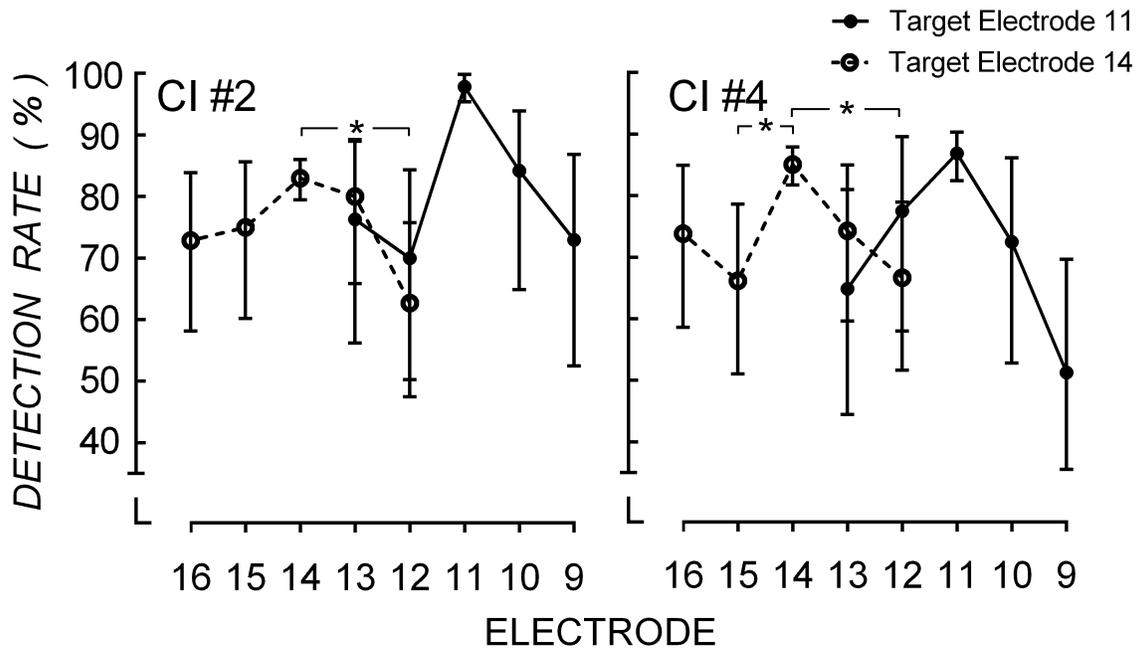


Figure 7. Shifted target experiment in two subjects. Errors bars show 99% CIs and * indicates a significant difference between target and probe detection rates for the condition when electrode 14 was the target. Results with electrode 11 receiving the target stimulation are the same as shown in Figure 5.

