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# Reduction in spread of excitation from current focusing at multiple cochlear locations in cochlear implant users

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ABSTRACT

Channel interaction from a broad spread of excitation is likely to be a limiting factor in performance by cochlear implant users. Although partial tripolar stimulation has been shown to reduce spread of excitation, the magnitude of the reduction is highly variable across subjects. Because the reduction in spread of excitation is typically only measured at one electrode for a given subject, the degree of variability across cochlear locations is unknown. The first goal of the present study was to determine if the reduction in spread of excitation observed from partial tripolar current focusing systematically varies across the cochlea. The second goal was to measure the variability in reduction of spread of excitation relative to monopolar stimulation across the cochlea. The third goal was to expand upon previous results that suggest that scaling of verbal descriptors can be used to predict the reduction in spread of excitation, by increasing the limited number of sites previously evaluated and verify the relationships remain with the larger dataset. The spread of excitation for monopolar and partial tripolar stimulation was measured at 5 cochlear locations using a psychophysical forward masking task. Results of the present study suggest that although partial tripolar stimulation typically reduces spread of excitation, the degree of reduction in spread of excitation was found to be highly variable and no effect of cochlear location was found. Additionally, subjective scaling of certain verbal descriptors (Clean/Dirty, Pure/Noisy) correlated with the reduction in spread of excitation suggesting sound quality scaling might be used as a quick clinical estimate of channels providing a reduction in spread of excitation. This quick scaling technique might help clinicians determine which patients would be most likely to benefit from a focused strategy.


## 1. Introduction

Although cochlear implants (CIs) provide an understanding of open-set speech to deaf patients, CI users struggle in challenging listening conditions (e.g. noisy environments, competing voices and music perception). Commercially available implant devices have between 12 and 22 electrodes. Although CI users typically can discriminate single electrodes in isolation, when multiple electrodes are stimulated sequentially (such as in a speech coding strategy) interference across channels occurs (e.g. Srinivasan et al., 2012). This limitation is likely to be caused by the broad spread of excitation from stimulation of each of the electrodes in the cochlea. As a result, CI users perform as if they have only 4–8 channels of information (Friesen et al., 2001). However, more than 8 independent channels are needed in challenging listening situations (e.g. Shannon et al., 2004).

Clinically, stimulation in monopolar (MP) mode is typically used. With MP stimulation, active current is applied to an electrode in the cochlea and an extra-cochlear electrode is used as a ground. MP stimulation has been shown to produce a relatively broad spread of excitation (e.g. Bierer and Middlebrooks, 2002; Bierer, 2007). In order to reduce spread of excitation (and as a result, channel interaction), current focused stimulation modes have been proposed (e.g. Jolly et al., 1996; van den Honert and Kelsall, 2007; Landsberger and Srinivasan, 2009; Saoji et al., 2013; Wu and Luo, 2014). Partial tripolar stimulation (PTP) is a current focused stimulation mode in which active current is applied to an intra-cochlear electrode (the primary electrode) while out-of-phase current is applied to its two flanking electrodes at lower amplitudes to reduce

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the spread of current fields. The amplitudes of the current applied to each flanking electrode are determined by a coefficient σ which ranges between 0 and 1. Specifically, the current applied to the flanking electrodes are each σ/2 times the amplitude of the current given to the primary electrode. The remaining current (1- σ) is provided to the extra-cochlear electrode. The larger the value of σ, the greater the degree of current focusing. Although PTP stimulation generally provides a reduction in spread of excitation relative to MP stimulation, the degree of reduction is highly variable for different subjects (Landsberger et al., 2012; Fielden et al., 2013). A schematic of MP and PTP stimulation is presented in Fig. 1.

Landsberger et al. (2012) suggested that the reduction in spread of excitation can be predicted by the perceived differences according to scaled descriptors. Specifically, Landsberger et al. (2012) asked patients to scale the quality of single channel pulse trains with varying degrees of current focusing (i.e. σ) in terms of how "Clean", "Dirty", "Pure", "Noisy", "High", "Low", "Full", "Thin", "Flute-like" and "Kazoo-like" they sounded. An index was calculated to estimate the perceptual differences between descriptor pairs "Clean/Dirty", "Pure/Noisy", "High/Low", "Full/Thin" and "Flute/Kazoo". Index values near zero represented sounds for which focused and unfocused stimuli were perceived equally by the subject and were described equally by both descriptors in a descriptor pair. Index positive values suggested that one of the descriptors better described focused stimulation while the other descriptor in the pair better described unfocused stimulation. A significant correlation between the reduction in spread of excitation from current focusing and the indices corresponding to "Clean/Dirty", "Pure/Noisy", "High/Low", and "Flute/Kazoo" were found. No correlation was found between the reduction in spread of excitation and the "Thin/Full" index. However, the data in Landsberger et al. (2012) was limited in that it was collected only at a single electrode (Electrode 9). As the scaled descriptors approach is time efficient, a version of it could be implemented in a clinical setting. However, it is worth noting that knowing the reduction in spread of excitation has yet to be demonstrated to be clinically beneficial.

The present study was designed as a follow up study to Landsberger et al. (2012). The first objective for the present study was to determine if the reduction in spread of excitation observed from current focusing is dependent on cochlear region. If one cochlear region provides a greater reduction in spread of excitation from current focusing consistently across subjects (i.e. a greater reduction seen in the apex than in the base), a strategy which primarily provides a reduction in spread at the more beneficial location might be desirable. Current focusing could be applied in the region which is most likely to show benefit from focusing, but not in regions less likely to benefit from focusing. While applying focusing in a cochlear region that does not receive a reduction in spread of excitation is unlikely to be directly detrimental to performance, there are reasons not to apply focusing on these channels. One reason is that current focusing requires more current and therefore drains battery life more quickly. Another reason is that larger phase durations are often needed with focused stimulation which limits the overall stimulation rate.

The second objective for the experiment was to determine the variability in the reduction in spread of excitation across the cochlea. As measuring the reduction in spread of excitation via a psychophysical forward masking paradigm is a very time consuming process, typically the reduction has been measured at only one electrode per subject (e.g. Zhu et al., 2012; Landsberger et al., 2012; Fielden et al., 2013). However, when the reduction in spread of excitation is only measured at one location, it is unknown how representative that reduction is at other cochlear locations for that subject. It is worth noting that Bierer and Faulkner (2010) compared psychophysical tuning curves for MP and PTP stimulation at three locations. However, because this methodology estimates spread of excitation near threshold, it may not be an accurate measure of the relative spread of excitation between MP and PTP stimuli at a comfortably loud level. Srinivasan et al. (2010) measured the difference between Monopolar Virtual Channels (MPVCs) and Quadrupolar Virtual Channels (QPVCs) at three cochlear locations and was unable to detect any systematic difference across cochlear locations. However, the study examined the sharpness of the peak of two virtual channel modes and therefore cannot specifically predict PTP reduction in spread of excitation. In the present study, we measure the reduction in spread of excitation when changing from MP to PTP stimulation modes at five locations across the cochlear implant array to determine the variability in reduction. If the variability across cochlear locations is small for all subjects, then knowing the reduction of spread of excitation at one location for a given subject would likely predict the reduction in spread of excitation at another location in the cochlea for the same subject. However it is worth noting that there may still be localized regions which may provide different outcomes, such as local dead region, or an electrode which is physically more distant from the site of neural stimulation.

A third motivation was to further test the relationship between the reduction in spread of excitation and sound quality scaling

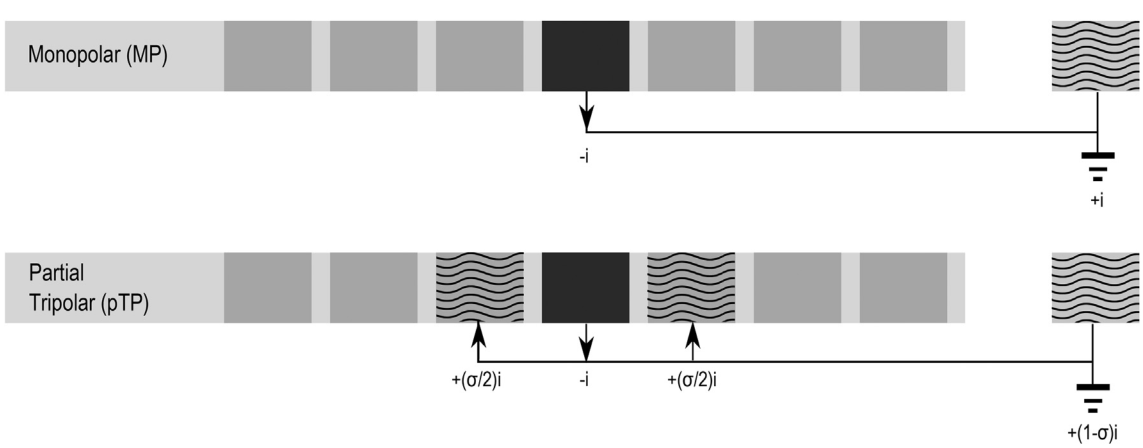


**Fig. 1.** Schematic of MP and PTP stimulation. Black color shows the active electrode, while the electrode outside of the array with a pattern denote the extracochlear returning electrode. In the partial tripolar schematic the two electrodes with the pattern next to the active electrode denote the flanking electrodes which have an out-of-phase stimulating current.

observed in Landsberger et al. (2012). As the sound quality scaling is very time efficient, if the relationship between the reduction in spread and sound quality scores is strong, then sound quality scaling could be a clinically implementable method of determining reduction in spread. However, the data in Landsberger et al. (2012) was limited to only 6 data points (six subjects at only one electrode). In the present study, we collected sound quality data at five electrodes with eight subjects which could be correlated with the reduction in spread of excitation measured while addressing the first two motivations. Presumably the new data set would provide stronger support (or demonstrate limitations) of the potential relationship between the reduction in spread of excitation and sound quality scaling.

Two experiments were performed in the present study. The first experiment was designed to address the first two motivations. In the first experiment, the spread of excitation for both MP ($\sigma = 0$) and PTP ($\sigma = 0.75$) stimulation modes was measured at multiple locations across the cochlea. The second experiment was designed to address the third motivation. In the second experiment, the sound quality of MP and PTP stimulation was scaled for all of the stimuli used in the first experiment. This data set allows for correlation of the reduction in spread of excitation measured in experiment 1 with the sound quality scaling. If the perceptual differences can predict reductions in spread of excitation, then asking a patient about the perceptual quality of single electrode pulse trains could be used clinically to determine sites of stimulation which might benefit from a reduction in spread of excitation.

## 2. Methods

### 2.1. Subjects

Eight post-lingually deafened users of the Advanced Bionics CII or HiRes 90K cochlear implants participated in this study conducted at the House Research Institute. All subjects were implanted with the HiFocus 1J electrode array without the use of the positioner. Six of the eight subjects (C1, C3, C4, C7, C8, and C9) also participated in the previous study by Landsberger et al. (2012). IRB approval was given by the St. Vincent Hospital Institutional Review Board. Subject specific information is provided in Table 1.

### 2.2. Stimuli

Stimuli consisted of cathodic-first bi-phasic single channel pulse trains presented in either MP or PTP stimulation modes. All PTP stimuli were presented with $\sigma = 0.75$. Pulse trains were presented at a rate of 1000 pulses per second (pps). The phase duration was set to 226.275 μs to maximize the probability that all PTP stimuli could be presented within device compliance limits. As in Srinivasan et al. (2013), the maximum amplitude considered to be in compliance was calculated using the formula ($7300/[R_{access\,k\Omega} + PhaseDur_{\mu sec} * 0.01]$). Impedance values for each electrode were available for all subjects except C19. Each of the stimuli for which impedance values were available were well under compliance limits. Although impedance measurements were not available for C19, the electrode with highest amplitude tested (Electrode 8 at 320 μa) would require an impedance of 21 kΩ to be out of compliance. Therefore it is unlikely but possible that some stimulation for C19 was out of compliance.

### 2.3. Experiment 1: estimating spread of excitation using forward masking

In the first experiment, the spread of excitation of equally loud MP and PTP maskers on electrodes 4, 6, 9, 10, and 12 were measured using the forward masking protocol. Before measuring spread of excitation (see Section 2.3.3), the electrical dynamic range needed to be estimated (see Section 2.3.1) and the amount of current required to create equally loud stimuli needed to be measured (see Section 2.3.2).

In the previous experiment (Landsberger et al., 2012) we measured forward masked curves for maskers on electrode 9 for MP and PTP stimuli using the same protocol as in this study for 6 subjects (C1, C3, C4, C7, C8, and C9). Therefore, for those six subjects, the forward masked data for the masker on electrode 9 was taken from Landsberger et al. (2012) while the forward masking data for maskers on electrodes 4, 6, 10, and 12 were newly collected for this manuscript. Forward masking was measured for maskers on electrodes 4, 6, 9, 10, and 12 for the two subjects not previously tested (C14 and C19) in Landsberger et al. (2012).

#### 2.3.1. Estimation of dynamic range

Stimuli with a duration of 300 ms were used to estimate the dynamic range for electrodes 2, 4, 6, 7, 8, 9, 10, 11, 12 and 14 in PTP mode and for electrodes 4, 6, 9, 10 and 12 in MP mode. Each stimulus was initially presented below threshold and was incremented in 5 μA steps until maximal comfort level was reached. Subjects reported the perceived loudness of the stimuli using a loudness scale from Advanced Bionics. The amplitudes of the current necessary to reach the loudness corresponding to “Barely Audible”, “Soft”, “Most Comfortable”, and “Maximal Comfort” were recorded. The amplitude corresponding to “Most Comfortable” was used for all stimuli presented during all the experiments, except the probes for which amplitudes were adjusted with an adaptive procedure to determine thresholds during the forward masking procedure.

#### 2.3.2. Loudness balancing

MP and PTP stimuli on electrodes 4, 6, 9, 10 and 12 were loudness balanced to a PTP pulse-train on electrode 9 at the “Most Comfortable” loudness previously estimated. Loudness balancing was conducted using a two interval forced choice double staircase procedure (1-up 3-down or 3-up 1-down).The subject was asked to report which of two stimuli was louder. One stimulus was always

**Table 1**
CI subject demographics.

| Subject | Gender | Age | Etiology | CI experience (years) | Array type | Prosthesis |
|---|---|---|---|---|---|---|
| C1 | M | 80 | Sudden sensorineural hearing loss | 10 | HiFocus 1J | CII |
| C3 | F | 57 | Genetic | 6 | HiFocus 1J | HiRes 90K |
| C4 | F | 65 | Cochlear otosclerosis | 7 | HiFocus 1J | HiRes 90K |
| C7 | F | 63 | Fever + streptomycin | 6 | HiFocus 1J | HiRes 90K |
| C8 | F | 65 | Hereditary (possible otosclerosis) | 4 | HiFocus 1J | HiRes 90K |
| C9 | M | 70 | Possible spinal meningitis | 10 | HiFocus 1J | CII |
| C14 | M | 48 | Maternal Rubella | 7 | HiFocus 1J | HiRes 90K |
| C19 | M | 63 | Sudden sensorineural hearing loss | 14 | HiFocus 1J | CII |

PTP stimulation on electrode 9 at a fixed amplitude, while the other stimulus (the target) was the stimulus being loudness balanced. The amplitude of the target stimulus was adjusted adaptively according to subject responses. Both stimuli had a duration of 300 ms with an inter-stimulus interval of 300 ms. The step size for the first two reversals was 1 dB and 0.5 dB for the next 8 reversals. The amplitude of the equally loud target stimuli was estimated by averaging the mean of the last six reversals for both traces. The loudness balancing procedure was repeated three times for each stimulus; the average amplitude of the three repetitions was used as the final amplitude estimate required to maintain equal loudness.

#### 2.3.3. Forward masking measurement

The masked and unmasked detection thresholds for 20 ms PTP probe stimuli ($\sigma = 0.75$) were measured using a two interval forced choice (2IFC) adaptive procedure (3-down 1-up). When measuring unmasked thresholds, one interval was silent and one contained the probe stimulus. Subjects were asked to select in which interval a sound was presented. The last six reversals of a total of 10 measured reversals were averaged to find an estimate of the threshold. Step size was 1 dB for the first six reversals and 0.2 dB for the last four reversals. Three threshold estimates were measured for each probe stimulus. The average of the three estimates was defined as the threshold level. Unmasked thresholds for PTP stimuli was found for electrodes 2, 4, 6, 8, 9, 10, 11, 12 and 14.

Masked thresholds were measured using a similar protocol. Again, a 2IFC adaptive procedure (3-down 1-up) was used. Both intervals contained a masker of 300 ms duration. One interval also had 20 ms PTP probe after a 5 ms masker-probe interval. Subjects were asked to identify which interval contained the probe stimulus. Maskers were either a MP or PTP stimulus at different electrodes: 4, 6, 9, 10 and 12. The masked probe thresholds were measured at the masker location and at locations corresponding to $\pm 2$ electrodes from the masker. Similar to the unmasked threshold measurements, the last 6 reversals of a total of 10 reversals were averaged to get a threshold estimate. The step sizes for the reversals were the same as in the unmasked threshold measurements. The average of the three masked threshold estimates was defined as the masked threshold level.

### 2.4. Experiment 2: qualitative rating of different levels of focusing

Five different pairs of descriptors ("Clean/Dirty", "High/Low", "Pure/Noisy", "Full/Thin" and "Flute-like/Kazoo-like") were used to rate the quality of single channel stimuli in either MP or PTP mode. These descriptors were the same ones used by Landsberger et al. (2012). In a trial, subjects were presented with one stimulus on either electrode 4, 6, 9, 10 or 12 and in either MP or PTP mode at the amplitude previously measured to be equally loud as a most comfortably loud PTP stimulation on electrode 9. Subjects were asked to scale how well the descriptor described the sound by clicking on a horizontal line as previously described by Landsberger et al. (2012). Subjects scaled the sound in a continuum that went from least-*descriptor* to most-*descriptor*. Qualitative ratings were scaled from 0 to 1 such that 0 corresponded with no agreement and 1 corresponded to complete agreement of the qualitative descriptor. Only two values of $\sigma$ were measured (0 for MP and 0.75 for PTP modes respectively). A total of 5 observations for each adjective at each level of current focusing (MP or PTP) were measured in a block for a given electrode. The order of electrodes used across blocks was randomized. A total of 15 observations (over 3 blocks) were made for each stimulus.

Due to the inability to continue testing subjects at the House Research Institute, the collection of data for some descriptors was not completed for subject C8 ("High/Low", "Full/Thin", and "Flute-like/Kazoo-like") and C14 ("Flute-like/Kazoo-like"). Subject C19 was not tested on electrode 12 because the corresponding electrodes were not included in his clinical map.

## 3. Results

### 3.1. Experiment 1: estimating spread of excitation using forward masking

The forward masked curves for both MP and PTP stimulation modes were calculated by subtracting the unmasked thresholds from the masked thresholds at each of the probe locations using dB units. The results were normalized to the masked threshold shifts at the masker electrode locations (electrodes 4, 6, 9, 10 and 12). The area under each masking curve was considered an estimate of the spread of excitation. The percent reduction in spread of excitation between MP and PTP stimulation for each subject and masker location was calculated as the difference in area under the curve between the corresponding MP and PTP forward masked curves.

The normalized forward masking curves for all eight subjects at each electrode tested are presented in Fig. 2. The percentage reduction in area under the forward masked curves is indicated for each subject and electrode. Reduction in spread of excitation ranges from −1.0% (subject C8) to 15.6% (subject C7) with a mean reduction of 5.5% when all subjects are considered. A total of 34 of 39 pairs of curves show a % reduction in area under the curve greater than 0. With the exception of C8, all subjects had a reduction in spread of excitation for at least 4 of the 5 electrodes tested.

There was a great deal of variability both across electrodes and subjects. The average reduction per subject across electrodes was 5.63% with an average standard deviation of 3.09%. Similarly, the average reduction per electrode across subjects was 5.46% with an average standard deviation of 1.00%. Fig. 3 shows the reduction in area of current spread between MP and PTP stimulation as a function of electrode (Fig. 3A) and subject (Fig. 3B). A two-way repeated-measures ANOVA with the factors of stimulation mode (MP vs PTP) and electrode showed an overall significant effect of mode of stimulation ($F(1,56) = 6.44$, $p = 0.014$) but no effect of electrode ($F(3,56) = 0.341$, $p = 0.796$) and no interaction between the two factors ($F(3,56) = 0.049$, $p = 0.986$).

### 3.2. Experiment 2: qualitative ratings of current focusing

Similar to Landsberger et al. (2012), adjective pair indices were calculated for each pair of descriptors ("Clean/Dirty", "Pure/Noisy", "High/Low", "Full/Thin", and "Flute-like/Kazoo-like"). Each index was calculated as the absolute value of the difference between the response for the two paired descriptors (e.g. "Clean/Dirty") for $\sigma = 0.75$ and $\sigma = 0$, as shown in the following equation for the "Clean/Dirty" index:

$$\text{Clean/Dirty Index} = \left|(\text{Clean}_{\sigma=0.75} - \text{Dirty}_{\sigma=0.75}) - (\text{Clean}_{\sigma=0} - \text{Dirty}_{\sigma=0})\right| \quad (1)$$

"Pure/Noisy", "High/Low", "Full/Thin", and "Flute-like/Kazoo-like" indices were calculated in the same manor. It is worth noting that this is the same equation that was used in Landsberger et al. (2012). However, the equation was misreported in Landsberger et al. (2012), although the values for the various indices were reported correctly.

The percentage of reduction in area of spread of excitation is plotted as a function of each adjective pair index at each electrode in Fig. 4. Each row represents the results for each electrode and each column represents the results for each pair of descriptors.

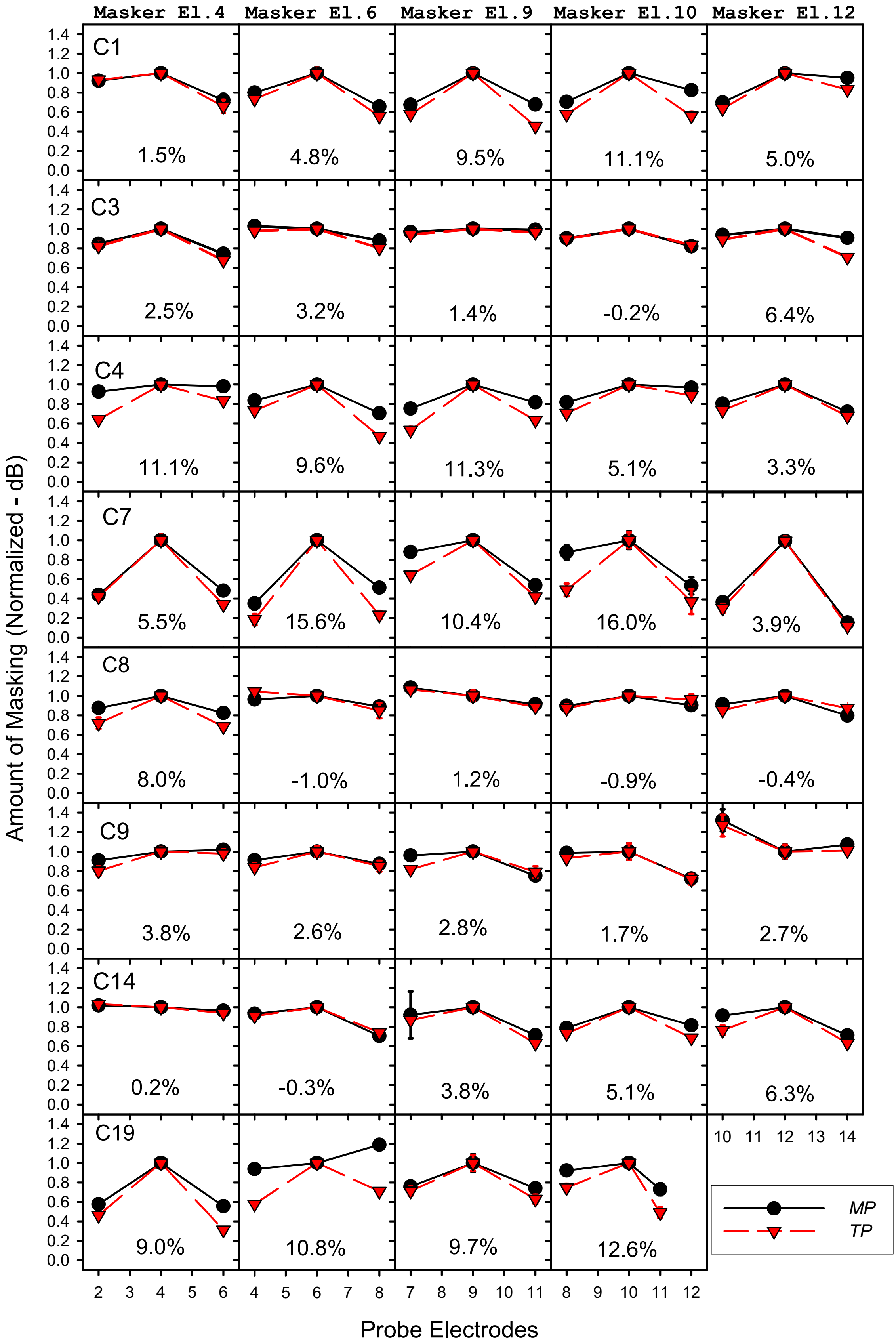


**Fig. 2.** Normalized forward masking curves for both MP and PTP maskers at different cochlea locations. Error bars represent ±1 standard error of the mean.

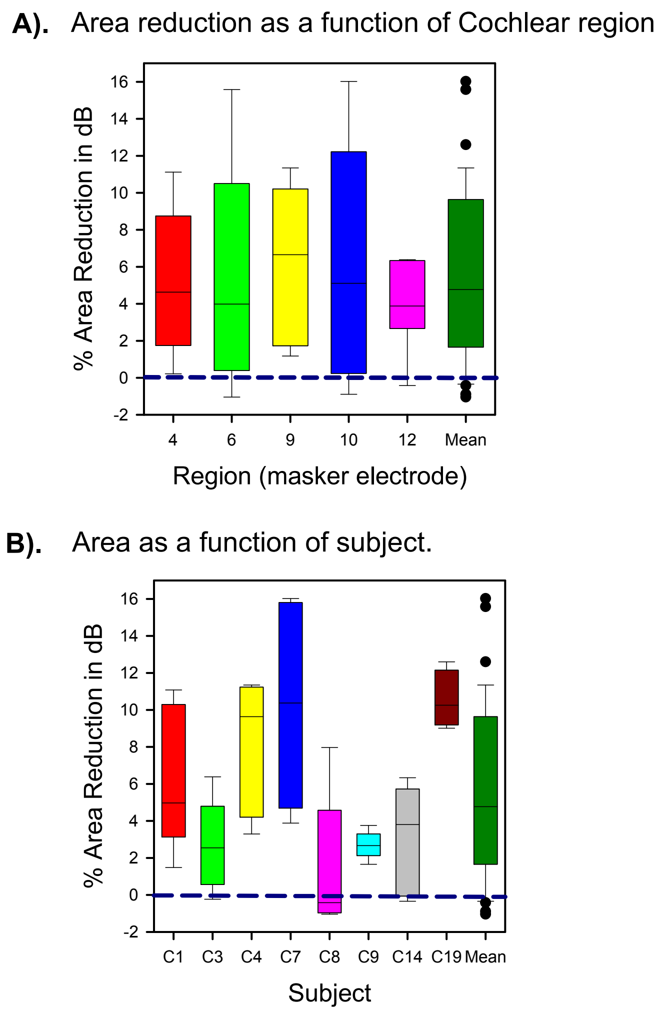


**Fig. 3.** Percentage reduction of the area under the normalized forward masking curves measured in dB units (1-PTP/MP) as a function of the cochlear region (A) and as a function of subject (B).

Results suggest that with a reduction in current spread larger than 5%, subjects tend to have an index value larger than 0.6 for the "Clean/Dirty" index. This pattern is less clear for other descriptor pairs. To determine if there is a relationship between reduction in spread of excitation and index value, data were collapsed across all electrodes for each index and Pearson correlations between percentage of reduction of area and each of the quality indices at all cochlear locations were calculated. A significant correlation was found between the reduction in area (decrement of spread of excitation) and the "Clean/Dirty" index ($r(37) = 0.620$, $p < 0.0001$) and the "Pure/Noisy" index ($r(37) = 0.429$, $p < 0.01$). No significant correlation was found for the remaining quality indices ($r(31) = 0.179$, $p = 0.319$ for "Full/Thin" index; $r(32) = 0.054$, $p = 0.762$ for "High/Low" index and $r(27) = 0.367$, $p = 0.05$ for "Flute-like/Kazoo-like" index). The correlations between the reduction in area and the "Clean/Dirty" and "Pure/Noisy" Index remain significant after Type I error corrections using Rom's method (Rom, 1990).

A summary of the reduction in area under the masking curve as a function of the "Clean/Dirty" index is shown in Fig. 5. The data can be separated into two quadrants. Subjects who have a reduction in spread of 5% or larger have larger "Clean/Dirty" index (red symbols), while if the reduction in area is less than 5%, the index is less than 0.6.

## 4. Discussion

The results of the present experiment demonstrate that PTP typically (34 out of 39 times) reduces spread of excitation compared to MP stimulation. These results are promising in that using a current focusing technique seems likely to provide a narrower spread of excitation and reduced channel interaction in a sound coding strategy.

The first objective, to determine if there are systematic differences in reduction in spread of excitation across the cochlea, is addressed in Fig. 3A. These data suggest that from a spread of excitation perspective, there is no inherent advantage (or disadvantage) to providing current focusing in any given cochlear region. However, it is worth considering that benefits from a reduction in spread may vary across cochlear locations based on the importance of the information carried at a given cochlear location, even if psychophysical results are similar at all locations. For example, apical and middle electrodes in the array may provide more important speech information than the basal electrodes, and therefore patients might benefit more from a reduced spread of excitation at apical and middle locations. Alternatively, when designing a strategy in which focusing is applied to a subset of electrodes, the selection of electrodes could be determined by patient specific parameters and not just cochlear location. For example, Bierer and Faulkner (2010) demonstrated that psychophysical tuning curves were sharper on channels with low PTP thresholds. Therefore, one might consider selecting channels with low PTP thresholds for receiving current focusing. In the present manuscript, no significant correlation was observed between PTP unmasked thresholds and area under the forward-masked threshold curve for either the MP or PTP maskers. Additionally, even with 8 subjects, only one subject demonstrated a significant correlation between PTP thresholds and reduction in spread of excitation. (C14; $r(3) = -0.984$, $p < 0.003$).

The second objective of the manuscript was to evaluate the variability of the reduction in spread of excitation across the cochlea. If the variability was small, measuring the reduction in spread of excitation at one electrode would provide a strong predictor to the reduction in spread of excitation. The average standard deviation of the reduction across electrodes was 3.09%, which is large relative to the average reduction across electrodes, which was 5.63%. The standard deviation for all reductions in spread (across cochlear locations and subjects) is not much larger at 4.63%. Therefore, knowing the reduction in spread of excitation at a single electrode provides little predictive power as to the reduction in spread that would be found at other cochlear locations for the same subject. If knowing the reduction of spread of excitation is important in either a clinical or research setting, it is important to measure at each location in question.

The cause of the variability in reduction with current focusing is unknown. One possible factor is the degree of local neural survival. If local neural survival is poor, then the only way to reach an adequate loudness may be to increase the current spread until a broader spread of excitation is reached. As an increase in amplitude (with or without current focusing) provides a broader spread of excitation (e.g. Chatterjee and Shannon, 1998), in the case of poor local neural survival, it may require that the amplitude of the focused stimulation be increased until an equivalent spread of excitation to a MP stimulus is reached in order to produce an equal loudness. Conversely, at regions with dense neural survival, focused stimulation may reach a given loudness by stimulating a distribution of neurons closer to the electrode than an equivalently loud MP stimulus. This idea is consistent with Bierer and Faulkner's (2010)

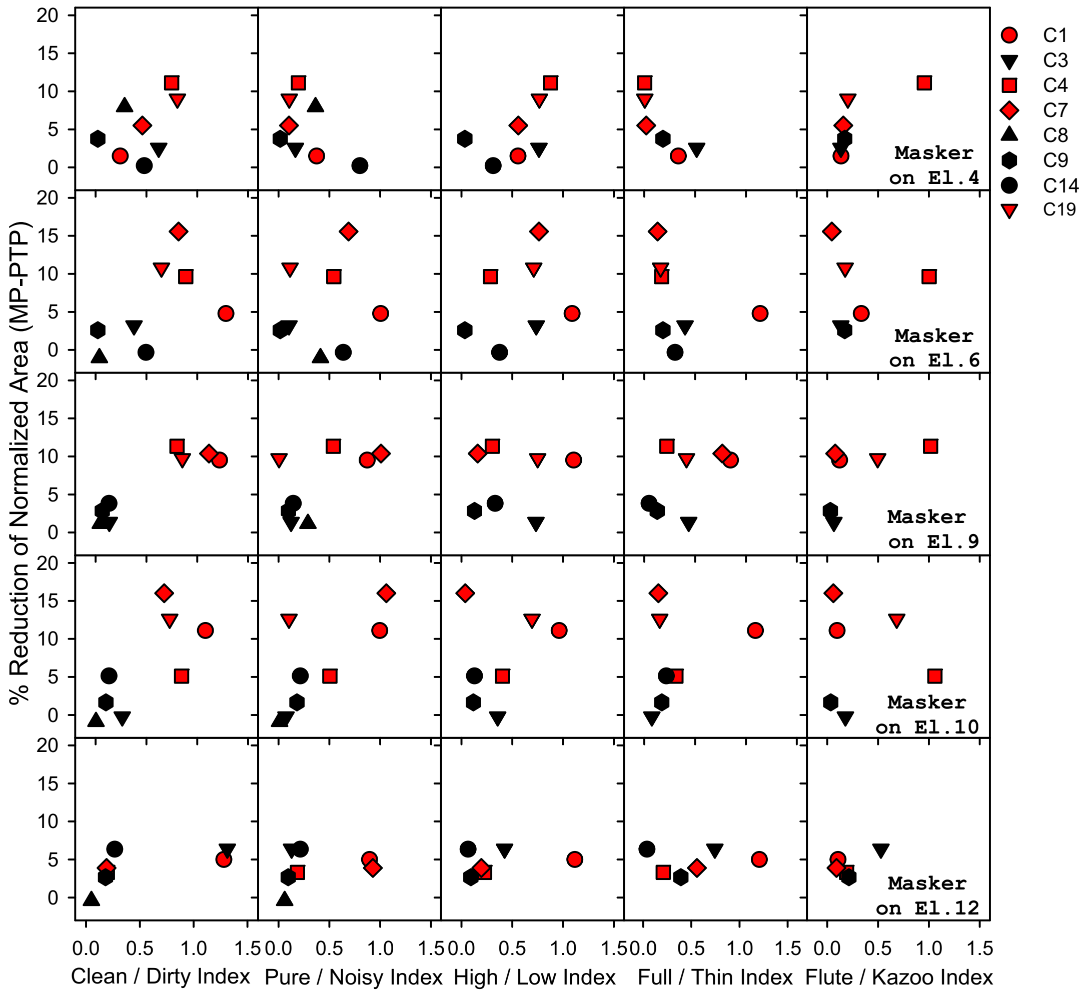


**Fig. 4.** Percentage reduction of the area under the normalized forward masking curves as a function of the different descriptors indices for all subjects tested. Different rows of plots show the results for different masker positions while the columns show the results for each descriptor pair.

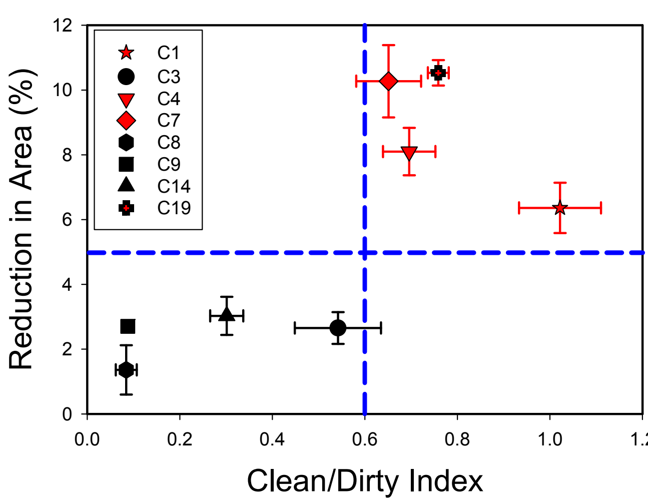


**Fig. 5.** Reduction in area of spread of excitation as a function of the "Clean/Dirty" index for each subject. Red color shows denotes the subjects that have larger reductions in spread of excitation and a larger index value, while black denotes the subjects that have a reduction of less than 5% and an index of less than 0.6. Error bars represent ±1 standard error of the mean. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

findings that channels with low PTP thresholds (presumably representing better or closer local neural representation) produced psychophysical tuning curves that were sharper than those observed on channels with high PTP thresholds (presumably representing worse or more distant neural representation.)

Srinivasan et al. (2013) found speech in noise performance with a PTP ($\sigma = 0.75$) speech processing strategy was better than with a parametrically equivalent MP strategy for all six subjects tested. The results were initially surprising because of the reductions in spread of excitation previously estimated at one electrode (Electrode 9; Landsberger et al., 2012) for 5 of the 6 subjects. Of those subjects, three (C3, C8, and C9) had relatively small reductions in spread of excitation and therefore might not be predicted to benefit from a focused strategy. However, as the reduction in spread of excitation at one electrode does not well predict the reduction in spread of excitation at other locations, it is possible that the benefit observed in Srinivasan et al. (2013) was dependent on a reduction in spread of excitation from another cochlear region. All six subjects tested in Srinivasan et al. (2013; C1, C3, C7, C8, C9, and C14) were tested in the current manuscript and showed that the greatest reduction in spread was not at electrode 9. These results further emphasize the importance of knowing the reduction of spread of excitation at multiple electrodes instead of extrapolating from one location. No significant correlations were found between the improvements in both HINT sentences in noise and digits in noise from Srinivasan et al. (2013) with the mean and maximum reduction in spread of excitation measured in the present study. Similarly, no significant correlations were detected between the improvements in both HINT sentences in noise and digits in noise with the reduction in spread of excitation associated with any electrode number. Although the reduction in spread of excitation did not predict improvements in performance, the absolute spread of excitation predicted performance with HINT in noise. Specifically, the mean, maximum and minimum spreads of excitation with MP stimulation were correlated with performance with the MP strategy ($r(3) = -0.987$, $p = 0.0018$; $r(3) = -0.925$, $p = 0.03$; $r(3) = -0.994$, $p = 0.0006$ respectively). Similarly, the mean, maximum and minimum spreads of excitation with PTP stimulation were correlated with performance with HINT in noise with the PTP strategy ($r(3) = -0.994$, $p = 0.00056$; $r(3) = -0.917$, $p = 0.036$; $r(3) = -0.987$, $p = 0.0019$ respectively.) All of these correlations with performance with HINT in noise remain significant after Type I error correction with Rom's method (1990). However, after Type I error, no significant relationship was found between the mean, maximum, or minimum spreads of excitation with the digits in noise performance for either MP or PTP stimulation modes. Furthermore, when evaluated either with HINT in noise or digits in noise, neither the MP nor the PTP speech in noise scores were correlated with the improvement obtained by switching from a MP to PTP strategy.

At the suggestion of McKay (2012), we analyzed the forward masked curves in this experiment in dB instead of μA. However, the curves (and calculations) in Landsberger et al. (2012) were in μA, so it was necessary for us to reanalyze the data from Landsberger et al. (2012) in dB to allow a comparison between the two data sets. The converted data is plotted in Fig. 6. The percentage reductions in spread of excitation observed in Landsberger et al. (2012) range from 14% to 167% bigger than the corresponding reduction in this experiment for the same subject and electrode. Presumably the differences observed between the two experiments were caused by the number of probe locations used to estimate the shapes of the curves. Although the reductions in area observed were larger for the Landsberger et al. (2012) analysis, the reductions in area between the Landsberger et al. (2012) analysis and the present analysis were highly correlated ($r(5) = 0.941$, $p = 0.005$)) suggesting that measuring spread of excitation with only the three points was similarly sensitive to detecting a reduction in spread of excitation as the estimate with seven points.

The third goal of the present research was to evaluate if a quick descriptor scaling task could be used to predict the reduction in spread of excitation. In Landsberger et al. (2012), data suggested that on one electrode location and six subjects, percept scaling could be used to predict the reduction of spread of excitation. In the present study, we used a similar scaling protocol for more subjects at multiple cochlear locations to determine if the relationship is maintained. In the present experiment, subjects were only asked to scale MP and PTP ($\sigma = 0.75$) stimuli while in Landsberger et al. (2012) PTP with multiple levels of σ were perceptually scaled. Only MP and PTP ($\sigma = 0.75$) results were used to calculate the index in both studies, although subjects had to scale additional PTP stimuli ($\sigma = 0.125$, 0.25, 0.375, 0.5, and 0.625) in Landsberger et al. (2012). In the present study even after Type I error correction the correlation for “Pure/Noisy” and “Clean/Dirty” pairs with spread of excitation remained significant, suggesting that the quicker perceptual scaling task for adjective pairs “Pure/Noisy” and “Clean/Dirty” is useful for predicting a reduction in spread of excitation. Fig. 7, shows the relationship between the indices calculated in both studies for the same group of subjects (C1, C3, C4, C7, C8 and C9 at electrode 9). A strong correlation is observed between the two studies for “Pure/Noisy” ($r(4) = 0.899$, $p = 0.0146$) and “Clean/Dirty” ($r(4) = 0.990$, $p = 0.00015$) indices, but only the “Clean/Dirty” index correlation is statistically significant after Type I error correction using Rom's method (Rom, 1990). These combined results suggest that a “Clean/Dirty” index calculated based on measurements with only MP and PTP ($\sigma = 0.75$) stimuli provides both a reasonable predictor for a reduction in spread of excitation with current focusing, but also provides a good estimate of a “Clean/Dirty” index calculated based on scaling data that included more stimuli which may allow better judgment of changes in quality as in Landsberger et al. (2012). Therefore, it seems likely that using a “Clean/Dirty” index would be a useful tool to quickly estimate if there is a reduction in spread of excitation for many patients. In other words, the “Clean/Dirty” index may be able to determine if an individual electrode provides a reduced spread of excitation in PTP mode, but will most likely not be useful for predicting the

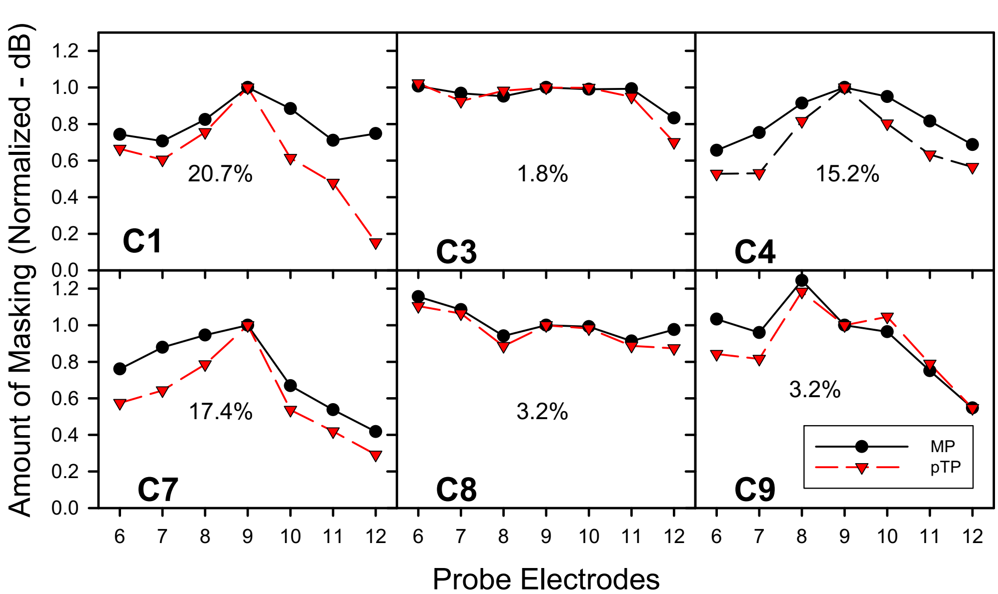


**Fig. 6.** Data from Landsberger et al. (2012) plotted in dB units. The percent reduction in area under the curves are also presented.

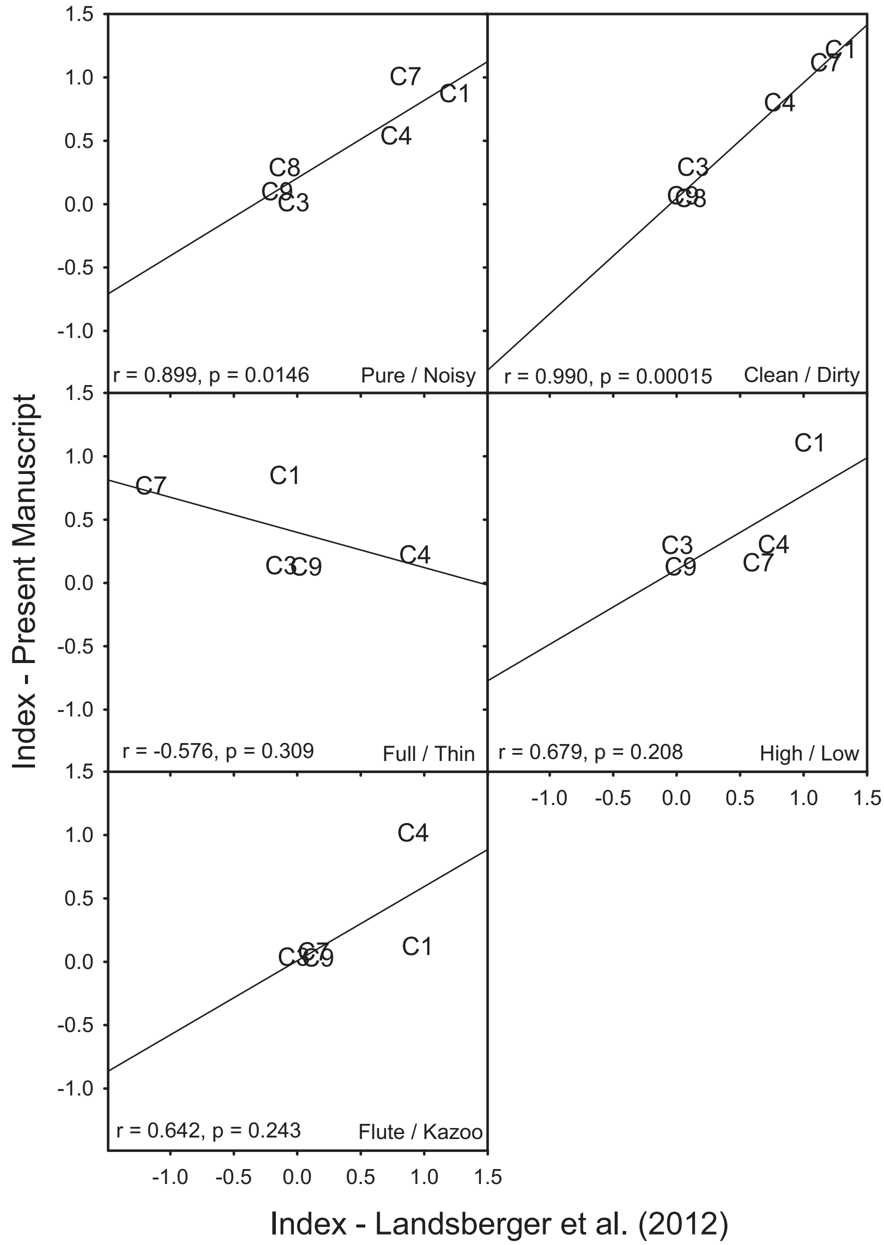


**Fig. 7.** Plot of indices calculated for descriptor scaling in both Landsberger et al. (2012) and the present manuscript. Each box represents index calculated for a descriptor pair ("Pure/Noisy", "Clean/Dirty", "Full/Thin", "High/Low" and "Flute-like/Kazoo-like"). The index value calculated in Landsberger et al. (2012) is plotted on the x-axis and the index value calculated in the present experiment is plotted on the y-axis. Subject codes are used to indicate points in the figure.

magnitude of the reduction, as suggested by Fig. 5.

In summary, PTP stimulation typically provides a reduced spread of excitation relative to MP stimulation. However, there is a great deal of variability in the degree of reduction in spread of excitation across subjects and cochlear locations. Variability between subjects and different locations within the same subject may be due in part to individual anatomical differences such as neural survival. Thus, it cannot be assumed that current focusing will provide a narrower spread of excitation compared to MP for a given subject or electrode. Furthermore, knowing the reduction in spread on a given electrode is insufficient to predict the reduction of spread at other electrodes. A quick scaling of how "Clean" and how "Dirty" a focused and an unfocused stimulation is, will likely provide a time efficient prediction of whether or not a reduction in spread of excitation is actually achieved with current focusing. This task can be performed clinically to assess in which cases and in which cochlear locations a given subject can take advantage of a speech processing strategy that includes current focusing.

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