Place-pitch discrimination of single- versus dual-electrode stimuli by cochlear implant users (L)[a]

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Simultaneous or near-simultaneous activation of adjacent cochlear implant electrodes can produce pitch percepts intermediate to those produced by each electrode separately, thereby increasing the number of place-pitch steps available to cochlear implant listeners. To estimate how many distinct pitches could be generated with simultaneous dual-electrode stimulation, the present study measured place-pitch discrimination thresholds for single- versus dual-electrode stimuli in users of the Clarion CII device. Discrimination thresholds were expressed as the proportion of current directed to the secondary electrode of the dual-electrode pair. For 16 of 17 electrode pairs tested in six subjects, thresholds ranged from 0.11 to 0.64, suggesting that dual-electrode stimuli can produce 2–9 discriminable pitches between the pitches of single electrodes. Some subjects demonstrated a level effect, with better place-pitch discrimination at higher stimulus levels. Equal loudness was achieved with dual-electrode stimuli at net current levels that were similar to or slightly higher than those for single-electrode stimuli. [DOI: 10.1121/1.1937362]

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I. INTRODUCTION

Cochlear implant (CI) listeners have access to a limited number of pitches associated with place of stimulation in the cochlea. For single-electrode stimulation, place pitch is constrained by the number of electrode contacts along the implanted array, typically 12–22 in contemporary devices. Additional factors such as poor neural survival can result in “indiscriminable electrodes,” further reducing the number of available pitches related to place of stimulation.

For some CI users, weighted stimulation of two adjacent electrodes can produce one or more intermediate pitches, thus increasing the total number of place-pitch steps available. This phenomenon was first demonstrated by Townshend *et al.* (1987), for simultaneous stimulation of two distant electrodes. Later, Wilson *et al.* (1993, 1994, 2003) used simultaneous stimulation of adjacent electrodes to produce intermediate pitches in four subjects with the Ineraid device. Finally, McDermott and McKay (1994) studied five subjects with the Nucleus-22 implant and showed that intermediate pitches could be generated when pulses on two electrodes were interleaved with a brief temporal separation rather than presented simultaneously.

None of the earlier studies specifically measured the number of discriminable pitches that could be generated for a given dual-electrode pair. However, one subject tested by Wilson *et al.* (2003) was able to distinguish 25% increments in the current weighting between electrodes 4 mm apart and one subject tested by McDermott and McKay could distinguish six dual-electrode stimuli between electrodes separated by 0.75 mm. Other data from the study by McDermott and McKay indicated considerable variability in place-pitch discrimination across individuals and electrode positions.

The purpose of the present study was to further evaluate place-pitch discrimination for simultaneous, dual-electrode stimulation of closely spaced electrodes. In addition to obtaining discrimination thresholds for single- versus dual-electrode stimuli, we sought to obtain preliminary information on the effects of stimulus level. Previous studies have shown that place-pitch discrimination improves with level for single-electrode stimuli (Pfingst *et al.*, 1999; McKay *et al.*, 1999) and a similar effect was anticipated for the task involving dual-electrode stimuli. We also wished to evaluate the effect of dual-electrode stimulation on loudness. In particular, we sought to determine whether a constant level of current produced the same loudness when the current was apportioned between two adjacent electrodes (dual-electrode stimulation) as when it was directed entirely to one electrode (single-electrode stimulation). Loudness summation was demonstrated in the McDermott and McKay study for non-simultaneous dual-electrode stimuli, but loudness effects were not evaluated in earlier studies using simultaneous, dual-electrode stimulation.

II. METHODS

Subjects were six postlingually-deafened adults with a Clarion CII cochlear implant. Relevant subject information is provided in Table I. Each subject had a HiFocus or HiFocus II electrode array, with 16 flat-plate electrode contacts arranged in a line with center-to-center distances of approxi-

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TABLE I. Description of subjects. Subject code, gender, age, duration of implant use, duration of deafness prior to implantation, and phonemes-correct score on NU-6 words in quiet.

Subj	M/F	Age (yrs)	Cl use (yrs)	Deaf (yrs)	NU-6 % phon
D01	M	56.1	2.9	26	65
D02	F	54.7	2.9	1	61
D05	F	73.9	2.3	3	40
D08	F	52.8	1.9	13	45
D10	F	50.4	1.9	8	87
D11	M	73.4	1.1	32	39
D18	F	65.4	1.1	19	5

mately 1 mm. All six subjects used the HiResolution speech processing strategy, which employs high-rate, nonsimultaneous pulsatile stimulation.

Experiments were controlled by a personal computer running custom programs written for the Bionic Ear Data Collection System (Advanced Bionics, 2003). Stimuli were 200 ms trains of 32.2 μs/ph, 1000 pulse/s, cathodic-first biphasic pulses, presented in monopolar mode. Pairs of adjacent electrodes in the apical, middle and basal regions of the electrode array were tested (electrodes 2-3, 7-8 and 12-13, respectively). For the single-electrode stimulus, the more apical electrode in the pair was stimulated alone. For the dual-electrode stimulus, both the apical and basal electrodes of the pair were stimulated simultaneously. The proportion of the total current directed to the more basal electrode for the dual-electrode stimulus was denoted as α, with α ranging from 0 (all current to the more apical electrode) to 1 (all current to the more basal electrode). The single- and dual-electrode stimuli used for measuring psychometric functions were balanced in loudness to a perceptual level of medium loud (ML) or medium soft (MS). Equal loudness levels were determined using a double staircase procedure (Jesteadt, 1980) with a reference stimulus that produced a loudness of ML or MS on the more apical electrode of the dual-electrode pair. Two or three equal-loudness estimates were averaged to obtain a final equal-loudness level for each dual-electrode stimulus.

Psychometric functions relating α to pitch discrimination sensitivity were obtained with a two-alternative forced-choice (2AFC) procedure. Functions were initially obtained using relatively large increments (α=0, 0.25, 0.50, 0.75, and 1.0); however, when preliminary threshold estimates indicated good place-pitch discrimination ($\alpha<0.25$), they were repeated using finer increments (α=0, 0.1, 0.2, 0.3, 0.4, and 0.5). On each trial, the single-electrode stimulus and dual-electrode stimulus were presented in random order, and the subject selected the interval with the higher-pitched sound. A correct response was scored when the subject chose the interval containing the dual-electrode stimulus. No feedback was given. Stimuli were presented in blocks of 50 or 60 trials, comprised of ten trials for each value of α in random order. At least five blocks were obtained for each condition, so that 50 or more comparisons were incorporated in the mean percent-correct score for each value of α. The mean scores were converted to d' values (Hacker and Ratcliffe, 1979) and linear interpolation was used to compute the value of α producing performance of $d'=1.16$ (equivalent to 79.4% correct).

Adaptive place-pitch discrimination thresholds were obtained for comparison to the psychometric function estimates using a 2AFC, 3-down, 1-up procedure that also estimated 79.4% correct performance ($d'=1.16$). The adaptive variable, α, was initially set to a value that allowed the single- and dual-electrode stimuli to be easily discriminated (typically, 0.5 or 0.7). It was then altered in steps of 0.05 for the first three reversals of the track and in steps of 0.025 for the remaining seven reversals. The place-pitch threshold was computed as the mean value of α for the final six reversals. Linear interpolation was used to estimate equal-loudness levels for values of α encountered during the adaptive track that were intermediate to those measured for the psychometric functions.

III. RESULTS AND DISCUSSION

Figure 1 shows psychometric functions and adaptive threshold estimates for the ML stimuli. For most subjects, data are shown for apical, middle, and basal electrode pairs.[1] Psychometric functions were generally well-behaved, showing monotonic increases in performance (d') with increasing values of α. In one case (D18, apical pair), the subject could not reliably discriminate any of the dual-electrode stimuli from the reference, single-electrode stimulus: The psychometric function was nearly flat and performance never reached the threshold criterion value of $d'=1.16$. Not surprisingly, this subject was unable to perform the corresponding adaptive pitch-discrimination task.

In general, there was good agreement between the threshold estimates based on the psychometric functions and the thresholds obtained with the adaptive procedure. The only exception occurred for subject D02 on the basal electrode pair, where the adaptive threshold (α=0.87) was significantly larger than the threshold based on the psychometric function (α=0.64). There was no obvious explanation for this discrepancy.

It is evident from Fig. 1 that place-pitch thresholds varied considerably across subjects and electrodes. Subjects D01 and D08 demonstrated small thresholds for all three electrodes ($\alpha<0.22$). Subjects D02, D05, and D11 demonstrated larger thresholds, on average, and their thresholds

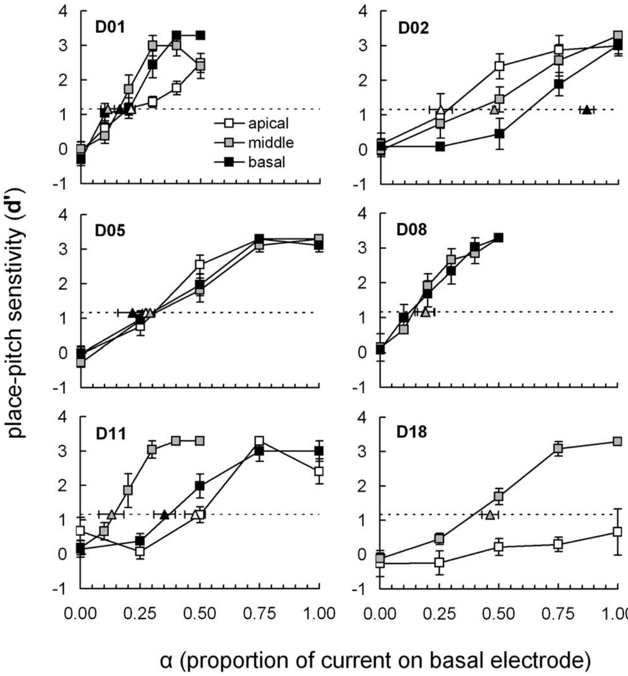

FIG. 1. Psychometric functions and adaptive thresholds for discrimination of single- versus dual-electrode stimuli for apical, middle and basal electrode pairs in six subjects. Stimuli are ML. Adaptive thresholds are represented by the filled triangles. The dashed line indicates the threshold criterion of $d'=1.16$.

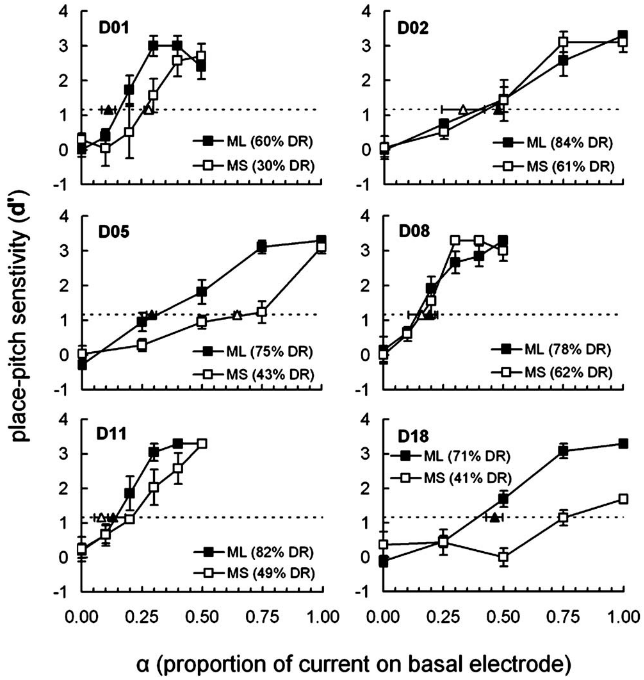

FIG. 2. Psychometric functions and adaptive thresholds for discrimination of single- versus dual-electrode stimuli for one middle electrode pair in each of six subjects. Stimuli are ML or MS. Adaptive thresholds are represented by filled triangles. The dashed line indicates the threshold criterion of $d'=1.16$.

were more variable across electrodes. The remaining subject, D18, achieved a moderate threshold ($\alpha=0.35$) for the middle electrode but, as indicated earlier, was unable to reliably discriminate pitch differences on the apical electrode pair. There was no systematic relation between place-pitch sensitivity and the word recognition scores shown in Table I.

Figure 2 shows psychometric functions and adaptive threshold estimates at two loudness levels (ML and MS) for each subject's middle electrode pair. Two subjects (D05, D18) showed a clear level effect with better performance for the higher-level stimulus. The remaining subjects showed a smaller level effect (D01, D11) or no effect of level (D02, D08). On average, place-pitch sensitivity was significantly better for the ML stimulus than for the MS stimulus, as expected on the basis of previous single-electrode studies (one-tailed paired-comparison t test for thresholds estimated from the psychometric functions, $t=-2.22$, $df=5$, $p<0.05$).

Figure 3 shows representative loudness balance data for two subjects (D02 and D05) obtained for the ML and MS conditions depicted in Figs. 1 and 2. Current levels are expressed in the clinical units used by the Clarion device. Each data point reflects the average current level computed from two or three individual loudness-balance estimates. Differences among the individual estimates for a given condition were generally very small, averaging 1.74% (0.15 dB) across 19 loudness-balance functions in six subjects.

The current required to produce a medium loud (or medium soft) percept was generally similar for the two single electrodes of a given electrode pair ($\alpha=0$ and $\alpha=1$ conditions in Fig. 3). For about half of the loudness balance functions, the net current levels producing equal loudness for the intermediate, dual-electrode conditions fell along an imaginary line connecting the two end points. This indicates that the current requirements for the dual-electrode stimuli were equivalent to those for the single-electrode stimuli. Examples of this are seen in Fig. 3 for all of D05's loudness-balance functions and for D02's functions for the apical and basal electrode pairs. For the other half of the functions, data points for the dual-electrode conditions fell slightly above the imaginary line connecting the end points of the function, indicating that the dual-electrode stimuli required a higher net current level than the single-electrode stimuli. Examples of this occur for D02's middle electrode pair (MS and ML conditions). A one-way, repeated measures analysis of variance on ranks was applied to the data for 19 functions in six subjects after normalization to adjust for current differences in the single-electrode stimuli. This analysis showed that the dual-electrode stimuli required significantly higher current

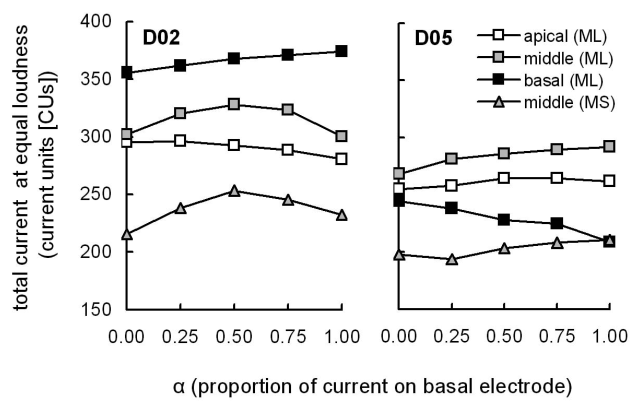

FIG. 3. Loudness balance functions for two subjects.

levels, on average, than the corresponding single-electrode stimuli (chi-squared=28.8, $df=4$, $p<0.001$). Post-hoc tests indicated that current levels for the dual-electrode stimuli were not significantly different for the three values of α (0.25, 0.50, and 0.75). Although the dual-electrode stimuli required higher net current levels on average than the single-electrode stimuli, the absolute magnitude of these differences was small. The largest difference observed between the measured value and the value expected from the single-electrode data was 1.1 dB (D02, middle electrode pair, MS) and the difference was greater than 0.5 dB in only one other instance (D02, middle electrode pair, ML).

The loudness effects observed here for simultaneous, dual-electrode stimulation contrast with those reported by McDermott and McKay (1994) for nonsimultaneous stimulation. In their study, each pulse of the dual-electrode stimulus required a 0.76–1.1 dB reduction in current amplitude to achieve equal loudness with the corresponding single-electrode stimulus; however, this corresponds to a net increase in total charge of approximately 5 dB for the dual-electrode stimulus (~6 dB increase for presentation of two stimuli less ~1 dB reduction). Simultaneous dual-electrode stimulation requires less total charge than nonsimultaneous stimulation because it involves the direct summation of field currents as compared to the summation of neural responses or loudness.

Comparison of the present results with those of McDermott and McKay (1994) suggest that average place-pitch discrimination is similar for simultaneous and nonsimultaneous dual-electrode stimulation. This appears to be true even though the underlying mechanisms are different: Nonsimultaneous stimulation involves integration of responses at the neural membranes or more centrally in the auditory system, whereas simultaneous stimulation involves summation of intracochlear current fields.

Although the present study evaluated the discrimination of single-electrode versus dual-electrode stimuli, it is likely that similar thresholds would be obtained for the discrimination of dual-electrode stimuli with different values of α. Further research is needed to confirm this assumption and to extend the present findings to a larger sample of subjects.

IV. CONCLUSIONS

(1) Dual-electrode stimulation can increase the number of place-pitch steps available to cochlear implant patients with contemporary devices. In the present study, place-pitch discrimination of adjacent electrodes was possible for 16 of 17 electrode pairs evaluated in six subjects. Thresholds for single- versus dual-electrode stimulation ranged from 0.11 to 0.64, suggesting that a two- to nine-fold increase in the number of place-pitch steps is possible with dual-electrode stimuli.

(2) Some subjects demonstrate a level effect in which place-pitch discrimination of dual-electrode stimuli improves with stimulus level. This effect is similar to the level effects observed for place-pitch discrimination with single-electrode stimulation.

(3) Equal loudness can be achieved with simultaneous, dual-electrode stimuli at net current levels that are similar to or only slightly higher than those for single-electrode stimuli.

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[1]Data for the apical electrode pair of subject D08 are not shown because the subject demonstrated a pitch reversal for these electrodes. Despite the pitch reversal, the psychometric function and adaptive thresholds showed good place-pitch resolution (thresholds of $\alpha=0.7$ and $\alpha=0.9$, respectively). Subject D18's basal electrode pair was not tested because the subject could not tolerate moderate or loud stimuli for electrodes in the basal portion of her array.

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