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Research paper

Modulation frequency discrimination with single and multiple channels in cochlear implant users

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ABSTRACT

Temporal envelope cues convey important speech information for cochlear implant (CI) users. Many studies have explored CI users' single-channel temporal envelope processing. However, in clinical CI speech processors, temporal envelope information is processed by multiple channels. Previous studies have shown that amplitude modulation frequency discrimination (AMFD) thresholds are better when temporal envelopes are delivered to multiple rather than single channels. In clinical fitting, current levels on single channels must often be reduced to accommodate multi-channel loudness summation. As such, it is unclear whether the multi-channel advantage in AMFD observed in previous studies was due to coherent envelope information distributed across the cochlea or to greater loudness associated with multi-channel stimulation. In this study, single- and multi-channel AMFD thresholds were measured in CI users. Multi-channel component electrodes were either widely or narrowly spaced to vary the degree of overlap between neural populations. The reference amplitude modulation (AM) frequency was 100 Hz, and coherent modulation was applied to all channels. In Experiment 1, single- and multi-channel AMFD thresholds were measured at similar loudness. In this case, current levels on component channels were higher for single-than for multi-channel AM stimuli, and the modulation depth was approximately 100% of the perceptual dynamic range (i.e., between threshold and maximum acceptable loudness). Results showed no significant difference in AMFD thresholds between similarly loud single- and multi-channel modulated stimuli. In Experiment 2, single- and multi-channel AMFD thresholds were compared at substantially different loudness. In this case, current levels on component channels were the same for single- and multi-channel stimuli ("summation-adjusted" current levels) and the same range of modulation (in dB) was applied to the component channels for both single- and multi-channel testing. With the summation-adjusted current levels, loudness was lower with single than with multiple channels and the AM depth resulted in substantial stimulation below single-channel audibility, thereby reducing the perceptual range of AM. Results showed that AMFD thresholds were significantly better with multiple channels than with any of the single component channels. There was no significant effect of the distribution of electrodes on multi-channel AMFD thresholds. The results suggest that increased loudness due to multi-channel summation may contribute to the multi-channel advantage in AMFD, and that overall loudness may matter more than the distribution of envelope information in the cochlea.

1. Introduction

In cochlear implants (CIs), low-frequency temporal envelope cues (<20 Hz) are important for speech understanding, while higher frequency envelope cues (80–300 Hz) are important for perception of voice pitch. Given the limited spectral resolution of the device, CI users strongly rely on temporal envelope cues for pitch-mediated speech tasks such as voice gender perception (Fu

Abbreviations: CI, cochlear implant; MDT, modulation detection threshold; F0, fundamental frequency; AM, amplitude modulation; AMFD, amplitude modulation frequency discrimination; DR, dynamic range; MDI, modulation detection interference

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et al., 2004, 2005; Fuller et al., 2014), vocal emotion recognition (Luo et al., 2007), tonal language perception (Luo et al., 2008), and speech prosody perception (Chatterjee and Peng, 2008). Temporal processing in CIs has been widely studied in terms of single-channel modulation detection thresholds (MDTs; Shannon, 1992; Busby et al., 1993; Chatterjee and Oba, 2005; Galvin and Fu, 2005, 2009; Pfingst et al., 2007; Won et al., 2011; Fraser and McKay, 2012; Green et al., 2012). Modulation detection is one of the few single-channel psychophysical measures that have been significantly correlated with speech perception for CI users (Cazals et al., 1994; Fu, 2002) and recipients of auditory brainstem implants (Coletti and Shannon, 2005), underscoring the importance of temporal processing to speech perception. Modulation detection has also been significantly correlated with modulation frequency discrimination (Chatterjee and Ozerbut, 2011), which is typically measured using envelope depths well above MDTs. The perception of changes in modulation frequency is highly relevant for perception of pitch cues in speech (e.g., voice gender, vocal emotion, lexical tones, prosody, etc.). Modulation frequency discrimination has been correlated with CI users' perception of lexical tones (Chatterjee and Peng, 2008; Luo et al., 2008), which depend strongly on perception of voice fundamental frequency (F0).

Previous CI studies have measured various aspects of amplitude modulation frequency discrimination (AMFD). Many studies have shown that, given a fixed amplitude modulation (AM) depth, single-channel AMFD thresholds generally improve as the current level is increased (Morris and Pfingst, 2000; Luo et al., 2008; Chatterjee and Ozerbut, 2011; Green et al., 2012). Guerts and Wouters (2001) found better single-channel AMFD with a fixed modulation frequency difference as the modulation depth was increased. However, Chatterjee and Peng (2008) found no consistent effect for modulation depths between 5% and 30% of the reference amplitude on single-channel AMFD thresholds. Efforts to enhance temporal envelope cues have shown mixed results for AMFD. Green et al. (2004) showed a small but significant advantage for perception of modulated frequency sweeps across multiple channels when the temporal envelope was sharpened ("sawsharp" enhancement). However, subsequently, Green et al. (2005) found poorer vowel recognition with the enhancement relative to the standard continuously interleaved sampling (CIS; Wilson et al., 1991) signal processing strategy, possibly due to its effect on spectral envelope cues. Hamilton et al. (2007) found that presenting modified temporal information to only one of six stimulated channels (rather than all channels as in Green et al., 2005), offered no clear advantage in a variety of speech recognition tasks. Landsberger (2008) found no significant difference in single-channel AMFD thresholds between sine, sawtooth, and sharpened sawtooth temporal envelopes. Kreft et al. (2010) found no significant difference in single-channel AMFD thresholds for pulse trains that were amplitude modulated by sine waves or by rectified sine waves, the latter of which was proposed to more closely resemble normal neural responses to low-frequency pure tones. Chatterjee and Ozerbut (2011) found some evidence of modulation tuning for AMFD thresholds, with increased sensitivity near 100 Hz, above and below which AMFD thresholds increased. When presented at a similar loudness level (i.e., 75% of the dynamic range, or DR), Green et al. (2012) showed no significant effect of carrier pulse rate on single-channel AMFD thresholds, despite better envelope representation with high carrier rates. Taken together, these single-channel studies suggest that, AMFD is strongly affected by current level and modulation depth, with modulation depth interacting with current level.

Although clinical CI speech processors provide multi-channel stimulation, very few studies have directly measured AMFD using multiple channels. Multi-channel envelope processing has mostly been measured using modulation detection interference (MDI) paradigms, in which CI users are asked to detect AM or discriminate between AM frequencies presented to one channel in the presence of competing AM on the same channel or other channels. Chatterjee (2003) found substantial modulation masking (defined as the difference in MDT between a dynamic and steady-state masker) even when masker channels were spatially remote from the target channel. Chatterjee and Oba (2004) found greater MDI for modulation detection when the modulation frequency of the interferer was lower than that of the target. Kreft et al. (2013) found a similar effect of masker-target modulation frequency for AMFD thresholds. In these studies, there was substantial off-channel masking, possibly due to the broad current spread associated with electric stimulation, and possibly due to envelope interactions beyond the auditory periphery.

Intuitively, multi-channel stimulation would be expected to offer some advantage in perception of coherent envelope information, relative to single-channel stimulation. Indeed, Guerts and Wouters (2001) found better AMFD thresholds with multiple channels than with any of the single component channels used for the multi-channel stimuli. However, no explicit adjustment was made for multi-channel loudness summation in Guerts and Wouters (2001). Work by McKay and colleagues (McKay et al., 2001, 2003) showed substantial multi-channel loudness summation independent of electrode spacing. As such, the multi-channel stimuli in Guerts and Wouters (2001) might have been louder than the single-channel stimuli, contributing to the multi-channel advantage. Previous studies (Morris and Pfingst, 2000; Luo et al., 2008; Chatterjee and Ozerbut, 2011; Green et al., 2012) have shown that single-channel AMFD improves with level (and by association, loudness). Interestingly, Galvin et al. (2014) found that multi-channel MDTs were better than MDTs with any of the single component channels. However, when the current levels were reduced in the multi-channel AM stimuli to match the loudness of the single-channel AM stimuli, multi-channel MDTs were significantly poorer than single-channel MDTs. As modulation detection is level-dependent, the reduced current levels required to accommodate multi-channel loudness summation resulted in poorer MDTs. It is unclear how multi-channel loudness summation may affect AMFD, while understanding perceptual mechanisms that may underlie multi-channel temporal processing is crucial and clinically relevant as CI speech processors are fit to accommodate multi-channel loudness summation.

In this study, single- and multi-channel AMFD was measured in CI users. Component electrodes were distributed to target relatively overlapping (narrow configuration) and non-overlapping neural populations (wide configuration). We hypothesized that AMFD would be better with the wide configuration due to multiple, relatively independent envelope cues, In Experiment 1, single- and multi-channel AMFD thresholds were measured at similar loudness. In this case, current levels were higher for single-channel AM stimuli than for multi-channel AM stimuli, due to multi-channel loudness summation. We hypothesized that for similarly loud AM stimuli, AMFD would be poorer with multiple than with single channels due to the reduced current levels needed to accommodate multi-channel loudness summation, similar to the MDT findings data from Galvin et al. (2014). In Experiment 2, single- and multi-channel AMFD thresholds were measured using the same summation-adjusted current levels for component channels. In this case, multi-channel AM stimuli were louder than the single-channel AM stimuli, due to multi-channel loudness summation. We hypothesized that, without adjustment for multi-channel loudness summation, AMFD would be better with multiple than with single channels, as in Guerts and Wouters (2001).

2. Methods

2.1. Subjects

Five adult, post-lingually deafened CI users participated in this experiment. All were users of Cochlear Corp. devices and all had more than 2 years of experience with their implant device. Relevant subject details are shown in Table 1. Four of the 5 subjects previously participated in a related modulation detection study (Galvin et al., 2014). Subjects S1, S2, S3, and S5 were bilateral CI users; S1 and S3 were tested using the first implant while S2 and S5 were tested using the second implant. All subjects provided written informed consent prior to participating in the study, in accordance with the guidelines of the St. Vincent Medical Center Institutional Review Board (Los Angeles, CA), which specifically approved this study. All subjects were financially compensated for their participation.

2.2. Stimuli

All stimuli were 300-ms biphasic pulse trains; the stimulation rate was 2000 pulses per second (pps) per electrode. The relatively high stimulation rate was chosen to ensure adequate sampling of the maximum AM frequency tested (356 Hz) and to approximate the default cumulative stimulation rate across all channels used in Cochlear Corp. devices (8 maxima × 900 pps/channel = 7200 pps cumulative rate). The pulse phase duration was 25 μs and the interphase gap was 8 μs. Monopolar stimulation was used. Two sets of three electrodes were selected for multi-channel stimuli to represent different amounts of channel interaction: a “wide” configuration consisting of electrodes 4, 10, and 16 and a “narrow” configuration consisting of electrodes 9, 10, and 11. The wide configuration was expected to target relatively independent neural populations and the narrow configuration was expected to target overlapping neural populations. All stimuli were presented via research interface (Wygonski and Robert, 2002), bypassing subjects' clinical processors and settings; custom software was used to deliver the stimuli and to record subject responses.

The electric dynamic range (DR) was first estimated for all single electrodes without AM. Absolute detection thresholds were initially estimated using a “counting” method, as is sometimes used for clinical fitting of speech processors. A number of 300-ms pulse train bursts (randomly selected between 2 and 5, with a 500 ms interval between bursts) were presented to the subject, who indicated how many bursts were heard. Stimulation initially began at sub-threshold levels and the current level was adjusted in 0.5 dB steps according to correctness of response (1-up/1 down). The detection threshold was the amplitude for the final of 4 reversals in current level. Maximum acceptable loudness (MAL) levels, defined as the “loudest sound that could be tolerated for a short time,” were initially estimated by slowly increasing the current level (in 0.2 dB steps) for 3 pulse train bursts until reaching MAL. Note that MALs are higher than comfort levels (C-levels) measured during clinical fitting of CI speech processors. Threshold and MAL levels were averaged across a minimum of two runs, and the DR was calculated as the difference in dB (re: 1 mA) between MAL and threshold.

Test electrodes were swept for loudness at 10% DR, 50% DR, and 100% DR (MAL) to ensure equal loudness, as is often done during clinical fitting of speech processors. The percent DR was calculated first in microamps and then converted to dB (re: 1 μA). During sweeping, 300 ms pulse trains were delivered to all electrodes (4, 9, 10, 11, and 16) in sequence (first from apex to base, and then from base to apex). The subject indicated which (if any) of the electrodes were louder or softer than the rest. If there were loudness differences across electrodes at 50% or 100% DR, the level of the different electrode was adjusted (up or down, as needed) by 0.4 dB (approximately 2 clinical units), and the electrodes were re-swept for loudness. If there were loudness differences across electrodes at 10% DR, the threshold level of the different electrode was adjusted (up or down, as needed) by 0.4 dB, and the electrodes were re-swept for loudness at 10% DR. After making all adjustments to obtain equal loudness, the final threshold, MAL and DR values for each electrode were recorded.

For the multi-channel stimuli, the component electrodes were optimally interleaved in time; the onset of each pulse was separated by 0.167 ms and the inter-pulse interval (between the offset of one pulse and the onset of the next pulse) was 0.109 ms. Because of loudness summation associated with multi-channel stimulation (McKay et al., 2001, 2003), the 3-channel stimuli were loudness-balanced to a common single-channel reference (electrode 10) presented at 50% DR (calculated in microamps then converted to dB re: 1 μA). The reference level of 50% DR was selected because the subsequent single-channel AMFD was measured for an AM depth of 100% DR (±50% DR re: reference of 50% DR). An adaptive two-alternative, forced-choice (2AFC), double-staircase procedure was used for loudness balancing (Jesteadt, 1980; Zeng and Turner, 1991); an ascending and descending track were randomly interleaved during each run. Stimuli were loudness-balanced without AM. In each trial for each track, two intervals were presented; the single-channel reference was randomly assigned to one interval and the multi-channel probe was assigned to the other. Subjects were asked to indicate which interval was louder, ignoring all other qualities of the stimuli. The current of the multi-channel probe was globally adjusted (in dB) according to subject response (2-down/1-up or 1-down/2-up, depending on the track), thereby adjusting the amplitude for each component electrode by the same ratio. The initial step size was 1.2 dB and the final step size was 0.4 dB. For each run, the final 8 of 12 reversals in current amplitude were averaged, and the mean of 2–3 runs was considered to be the loudness-balanced level. After adjustment for the multi-channel loudness summation, the current levels on the component electrodes were substantially reduced. These “summation-adjusted” current levels are indicated by an apostrophe throughout this paper (e.g., 4′). Note that the level adjustments for electrode 10 depended on the amount of summation associated with wide or narrow multi-channel configurations; hence the 10w′ and 10n′ designations.

Coherent sinusoidal AM was applied according to $f(t)*(1+m\sin(2\pi*f_m t))$, where f(t) is a steady-state pulse train, *m* is the modulation index, and f_m is the modulation frequency. Note that modulation was applied both above and below the carrier reference level. A 10-ms onset and offset ramp in amplitude was applied to all AM stimuli. The initial modulation phase was 180° for all stimuli. For the single-channel stimuli 4, 9, 10, 11, and 16, the modulation depth was between threshold and MAL (i.e., the entire DR). This maximum modulation depth was selected to provide strong

Table 1
CI subject demographics.

Subject	Age at testing (yrs)	Age at implantation (yrs)	Duration of deafness (yrs)	Etiology	Device	Strategy
S1	70	60	23	Genetic	N24	ACE
S2	79	77	35	Otosclerosis	N5	ACE
S3	28	26	11	Acoustic Neuroma	Freedom	ACE
S4	67	59	20	Meniere's/ Otosclerosis	Freedom	ACE
S5	78	76	8	Unknown	N5	ACE

envelope cues across different experimental conditions, as in Kreft et al. (2010, 2013). The same modulation depths (in dB) were used for the summation-adjusted component electrodes. Fig. 1 illustrates the current levels and modulation depths for three electrodes (wide configuration) for subject S3 (see Table 2 for exact values). For the original single-channel AM stimuli (left part of Fig. 1), AM depth was between threshold and MAL (100% DR). For the multi-channel AM stimuli (middle part of Fig. 1), current levels were reduced to accommodate multi-channel loudness summation. AM depth on each channel was the same (in dB) as for the original single channels (9.03, 9.58, and 9.18 dB for electrodes 4, 10, and 16, respectively). The perceptual range of the AM was presumably similar between these similarly loud single- and multi-channel AM stimuli, although this was not explicitly measured. For the summation-adjusted single-channel AM stimuli (right part of Fig. 1), the same current levels and modulation range (in dB) were used as for the multi-channel stimuli. However, these single-channel AM stimuli were much softer than the multi-channel AM stimuli (and the original single-channel AM stimuli). While the range of modulation (in dB) was the same for all component channels (regardless of the current level or the number of channels stimulated), the perceptual range of modulation was likely much reduced for the single-channel summation-adjusted AM stimuli. Here, peak AM current levels was approximately 50% of the original single-channel DR and the minimum AM current levels were substantially below the original single-channel thresholds (solid colored horizontal lines). Thus, the single- and multi-channel AM stimuli on the left half of Fig. 1 had similar overall loudness but different current levels, while the single- and multi-channel AM stimuli on the right half of Fig. 1 had different overall loudness but the same current levels on each component channel. Table 2 shows the test electrodes for each subject and condition, original threshold and MAL (in dB), summation-adjusted threshold and MAL (in DB), and the original DR (also the range of modulation for all AM stimuli, in dB). When measuring multi-channel AMFD, the current levels of the component channels were independently roved by ±1 dB to reduce any potential loudness differences among channels that may have escaped the initial loudness balancing procedure.

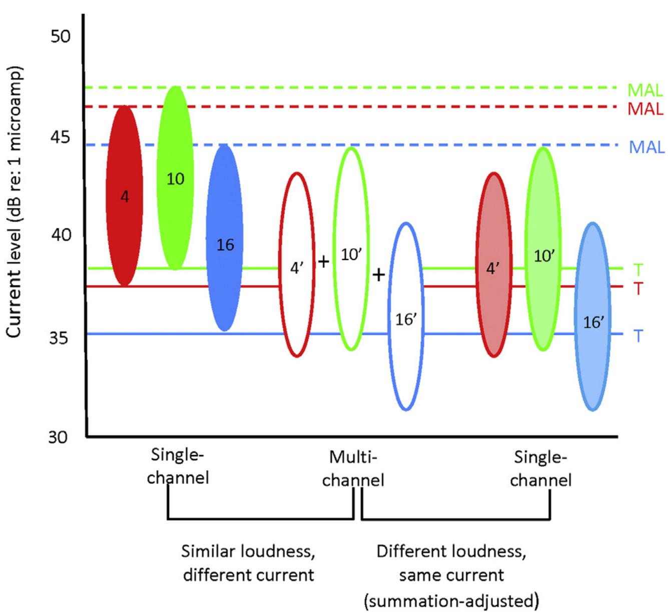

Fig. 1. Illustration of the current levels and modulation depths used for each experimental condition, for subject S3. The red, green, and blue ovals on the left side of the figure show the range of modulation for electrodes 4, 10, and 16 (original single-channel AM stimuli); the colored solid lines show the original thresholds (T) and the dashed colored lines show the original maximum acceptable loudness (MAL). These single-channel AM stimuli were similarly loud. The middle group of white ovals (with red, green, and blue outlines) shows current levels of the multi-channel AM stimuli after adjusting for multi-channel loudness summation. The right group of light red, green, and blue ovals shows the same summation-adjusted current levels for single-channel AM stimuli as used for the multi-channel AM stimuli. The left and middle groups of ovals were of similar loudness, but with different current levels, while the middle and right groups of ovals were of different loudness (multi-channel louder), but with the same current levels used on each component channel. Note also that the range of modulation (in dB) is the same for each component channel, regardless of experimental condition. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.3. Procedure

AMFD was measured using a method of constant stimuli. The reference modulation frequency was 100 Hz; the probe modulation frequency was 101, 102, 104, 108, 116, 132, 164, 228, or 356 Hz. A 3AFC procedure was used. While AM frequency may affect loudness (Vandali et al., 2013) given a fixed AM depth, these effects were expected to be small for the presentation levels and AM depths used in this study. To minimize the effects of loudness difference across AM frequencies, the current of the stimulus in each interval was globally roved by ±1 dB, similar to Chatterjee and Ozerbut (2011) and Kreft et al. (2010, 2013). Note that for multi-channel AM stimuli, this global roving was in addition to the component channel roving of ±1 dB, which was performed to reduce any potential loudness differences among channels. Two of the present subjects were asked to loudness-balance single-channel AM stimuli with 100 Hz versus 356 Hz AM rates and 100% DR modulation depth. Results showed no clear or consistent differences in loudness between the 100 Hz and 356 Hz AM stimuli.

During each experimental trial, the probe was randomly assigned to one of the three intervals and the reference was assigned to the remaining two intervals. The subject was asked to respond which interval was different. Subjects were instructed that the loudness of each interval might vary and to ignore loudness differences. Each test run contained 5 reference-probe comparisons for each probe; the reference-probe comparisons were randomized within each run. Three to six test runs were conducted for each condition, depending on subjects' availability for testing, resulting in a minimum of 15 and a maximum of 30 comparisons for each reference-probe combination; S1 and S4 completed 5 runs, S2 and S3 completed 6 runs, and S5 completed 3 runs. No trial-by-trial feedback as to the correctness of the response was provided. The test order for the different single- and multi-channel stimuli was randomized within and across subjects. In Experiment 1, AMFD was measured for similarly loud single- and multi-channel AM stimuli for both the wide and narrow configurations. In Experiment 2, AMFD was measured for single- and multi-channel AM stimuli using the same summation-adjusted current levels for each component channel, whether tested in a single- or multi-channel context.

3. Results

3.1. Loudness balancing of single- and multi-channel non-AM stimuli

Fig. 2 shows the current level adjustment needed to balance the loudness of the multi-channel non-AM stimuli to the single-channel non-AM reference (electrode 10 at 50% DR). The current level adjustment was calculated as the difference (in dB) between the single-channel reference and the multi-channel stimulus. Four out of the five subjects (S2 − S5) exhibited substantial multi-

Table 2
Threshold and MAL current levels in dB (re: 1 μA), with (El x; original single-channel levels) and without compensation for multi-channel loudness summation (El x'; summation-adjusted levels). For each experimental condition, AM was between these current levels. The DR also represents the range of modulation that was fixed for each electrode across conditions. For each subject, the mean and standard deviation of the threshold, MAL, and DR was calculated across all electrodes.

Subject	Configuration	Electrode	Single-channel (El x)		Single-channel,multi-channel (El x′)		DR
			Threshold	MAL	Threshold	MAL	
S1	Wide	4	46.02	58.87	43.97	56.82	12.85
		10	45.85	60.28	43.80	58.23	14.44
		16	44.08	58.17	42.03	56.12	14.09
	Narrow	9	45.67	59.75	44.24	58.33	14.09
		10	45.85	60.28	44.42	58.86	14.44
		11	44.40	59.75	42.98	58.33	15.35
		AVE	45.31	59.52	43.57	57.78	14.21
		STD	0.84	0.84	0.91	1.06	0.81
S2	Wide	4	42.54	51.20	38.48	47.14	8.66
		10	40.98	51.36	36.92	47.30	10.38
		16	41.14	50.58	37.08	46.52	9.44
	Narrow	9	41.44	51.53	36.81	46.90	10.09
		10	40.98	51.36	36.35	46.73	10.38
		11	40.83	51.05	36.20	46.42	10.23
		AVE	41.32	51.18	36.97	46.84	9.86
		STD	0.63	0.34	0.81	0.35	0.69
S3	Wide	4	37.62	46.65	34.02	43.05	9.03
		10	38.17	47.75	34.57	44.15	9.58
		16	35.12	44.30	31.52	40.70	9.18
	Narrow	9	38.28	48.06	33.37	43.15	9.79
		10	38.17	47.75	33.26	42.84	9.58
		11	38.79	47.75	33.88	42.84	8.96
		AVE	37.69	47.04	33.43	42.79	9.35
		STD	1.31	1.43	1.05	1.13	0.34
S4	Wide	4	46.65	54.96	36.20	46.42	10.23
		10	46.49	55.75	34.02	43.05	9.03
		16	44.45	55.75	34.57	44.15	9.58
	Narrow	9	46.97	55.92	40.94	49.89	8.95
		10	46.49	55.75	40.46	49.72	9.26
		11	46.49	57.01	40.46	50.98	10.53
		AVE	46.25	55.86	37.77	47.37	9.60
		STD	0.90	0.66	3.20	3.31	0.65
S5	Wide	4	41.65	50.90	37.76	47.01	9.25
		10	42.12	52.94	38.23	49.05	10.82
		16	40.86	50.74	36.97	46.85	9.88
	Narrow	9	41.02	52.63	36.66	48.27	11.61
		10	42.12	52.94	37.76	48.58	10.82
		11	41.80	53.10	37.44	48.74	11.30
		AVE	41.60	52.21	37.47	48.08	10.61
		STD	0.54	1.09	0.57	0.93	0.89

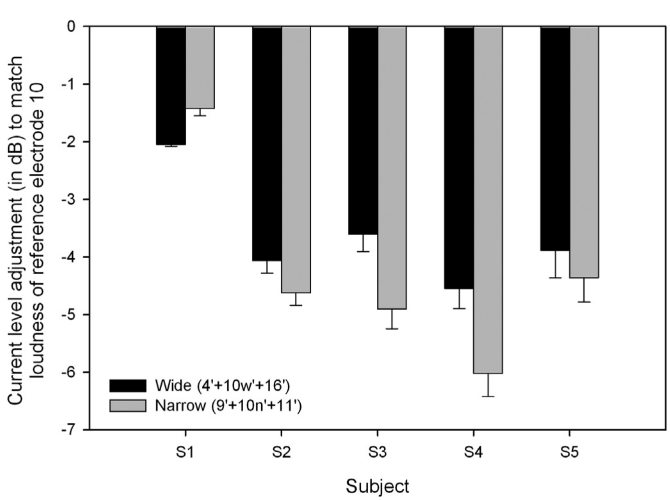

Fig. 2. Loudness balancing between single- and multi-channel non-AM stimuli. The black and gray bars show the current level adjustments (in dB) needed to equate loudness to single-channel reference (electrode 10 at 50% DR) for the wide and narrow multi-channel configurations, respectively. The error bars show 1 standard error.

channel loudness summation (3.6–6.0 dB), while subject S1 exhibited less summation (1.4–2.0 dB). The mean level adjustment was 3.6 dB and 4.3 dB for the wide and narrow electrode combinations, respectively. Four of the 5 subjects exhibited greater multi-channel loudness summation for the narrow than for the wide configuration. A one-way repeated measures analysis of variance (RM ANOVA), with electrode configuration as the dependent factor (wide or narrow) and subject as the random/blocking factor, showed no significant effect of electrode configuration [$F(1,4) = 2.95$, $p = 0.161$]; note that power was low (0.19), due to the low number of subjects. This is in agreement with findings by McKay et al. (2001), who found that loudness summation was not significantly affected by distribution of electrodes within the multi-channel stimulus.

3.2. Experiment 1: AMFD with similarly loud single and multiple channels

Fig. 3 shows AMFD (in percent correct) for similarly loud single- and multi-channel AM stimuli in the wide configuration, as a function of ΔF/F. Due to multi-channel loudness summation, the current levels for the single-channel AM stimuli were higher than

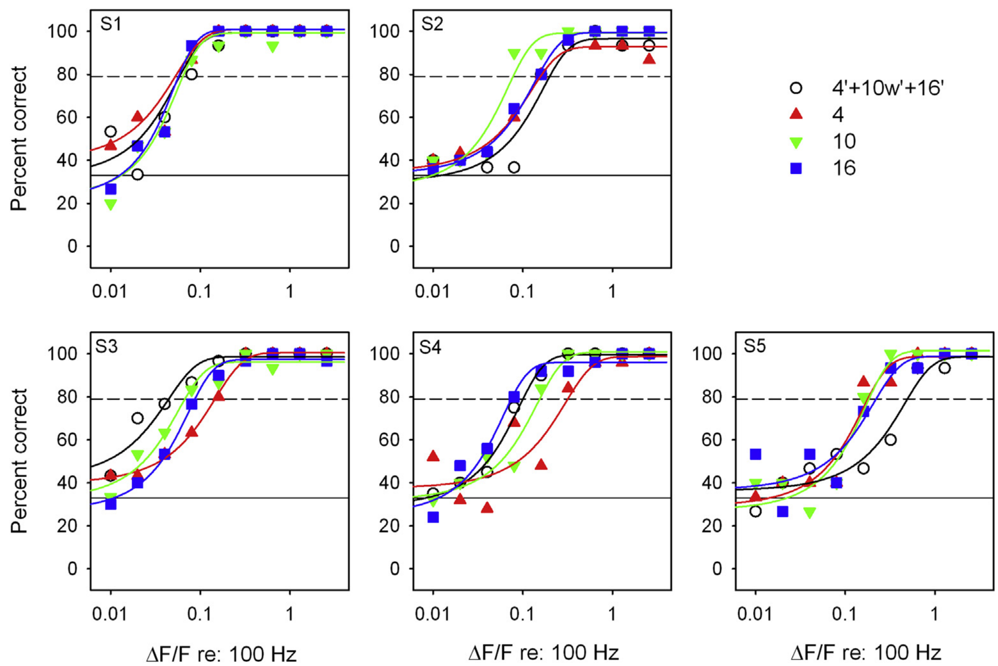

Fig. 3. AMFD for the wide electrode configuration with similarly loud single- and multi-channel AM stimuli. Each panel shows individual subject data. The open circles show multi-channel AMDT data, and the filled upward triangles, downward triangles, and squares show single-channel data for the basal, middle, and apical electrodes, respectively. The solid lines through the data show sigmoid fits. The dashed horizontal line shows threshold (79.4% correct) and the solid horizontal line shows chance level (33.3% correct).

those for the multi-channel AM stimuli. The open circles show multi-channel data and the filled symbols show single-channel data. The data were fit with sigmoid functions using Sigmaplot 11.0 (Systat Software Inc). In most cases, AMFD with single- and multi-channel stimuli were quite similar. For subject S3, AMFD was somewhat better with multiple than with single channels. For subject S5, AMFD with the multiple channels was markedly poorer than with single channels. In most cases, AMFD was well above chance level when ΔF/F was greater than 0.1.

Fig. 4 shows AMFD (in percent correct) for similarly loud single- and multi-channel AM stimuli in the narrow configuration, as a function of ΔF/F. Again, AMFD thresholds with single or multiple channels were quite similar, and were more similar than observed with the wide electrode configuration. Again, AMFD was well above chance level when ΔF/F was greater than 0.1.

Linear interpolations of the sigmoid functions shown in Figs. 3 and 4 were used to estimate the ΔF/F that corresponds to 79.4% correct; this threshold is sometimes used for adaptive measurements of AMFD (3-down/1-up; Levitt, 1971). Fig. 5 shows ΔF/F at threshold for individual subjects. The left and right panels show data for the wide and narrow combinations, respectively. As in Figs. 3 and 4, the single- and multi-channel AM stimuli were similarly loud. In general, ΔF/F at threshold was quite similar across single- and multi-channel AM stimuli, with the exception of S5 who exhibited a highly elevated multi-channel threshold in the wide configuration. Absolute ΔF/F at threshold also varied across subjects. Multi-channel ΔF/F at threshold values ranged from 0.05 (S3, wide configuration) to 0.71 (S5, wide configuration), and single-channel threshold values ranged from 0.05 (S1, electrode 9) to 0.32 (S4, electrode 4). One-way RM ANOVAs were performed on the data in Fig. 5, with stimulus (multi-channel and the three single channels) as the dependent factor and subject as the random/blocking factor. Because data were not normally distributed, a one-way RM ANOVA was performed on ranked data for the wide configuration. Results showed no significant effect of stimulus (Chi-square = 0.600 with 3 degrees of freedom; $p = 0.896$). For the narrow configuration, data were normally distributed. Results showed no significant effect of stimulus [$F(3,12) = 1.98$, $p = 0.170$].

Fig. 6 shows mean percent correct across all probe modulation frequencies for the wide (left panel) and narrow combinations (right panel), for single- and multi-channel AM stimuli. For multi-channel AM stimuli, mean values ranged from 57% correct (S5, wide configuration) to 86% correct (S3, wide configuration). For single-channel AM stimuli, mean values ranged from 64% correct (S5, electrode 9) to 83% correct (S1, electrode 9). One-way RM ANOVAs were performed on the data shown in Fig. 6, with stimulus (multi-channel and the three single channels) as the dependent factor and subject as the random/blocking factor. There was no significant effect of stimulus on mean percent correct for the wide [$F(3,12) = 0.20$, $p = 0.893$] or narrow configurations [$F(3,12) = 0.06$, $p = 0.979$]. Note that in both these analyses, power was very low (alpha = 0.05).

3.3. Experiment 2: AMFD with single or multiple channels using the same summation-adjusted current levels for the component channels

Fig. 7 shows AMFD (in percent correct) for the wide configuration as a function of ΔF/F. The open circles show multi-channel data (same data is shown in Fig. 3) and the filled symbols show single-channel data. Note that the current levels for each component electrode were the same whether for single- or multi-channel AM stimuli and that the multi-channel AM stimuli were substantially louder than the single-channel AM stimuli. With the exception of subject S1, multi-channel AMFD was much better than single-channel AMFD for all subjects.

Similar to Fig. 7, Fig. 8 shows AMFD (in percent correct) for the narrow configuration as a function as a function of ΔF/F. The open circles show multi-channel data (same data is shown in Fig. 4) and the filled symbols show single-channel data. Similar to the wide configuration, multi-channel AMFD with the narrow configuration was much better than single-channel AMFD for all subjects except

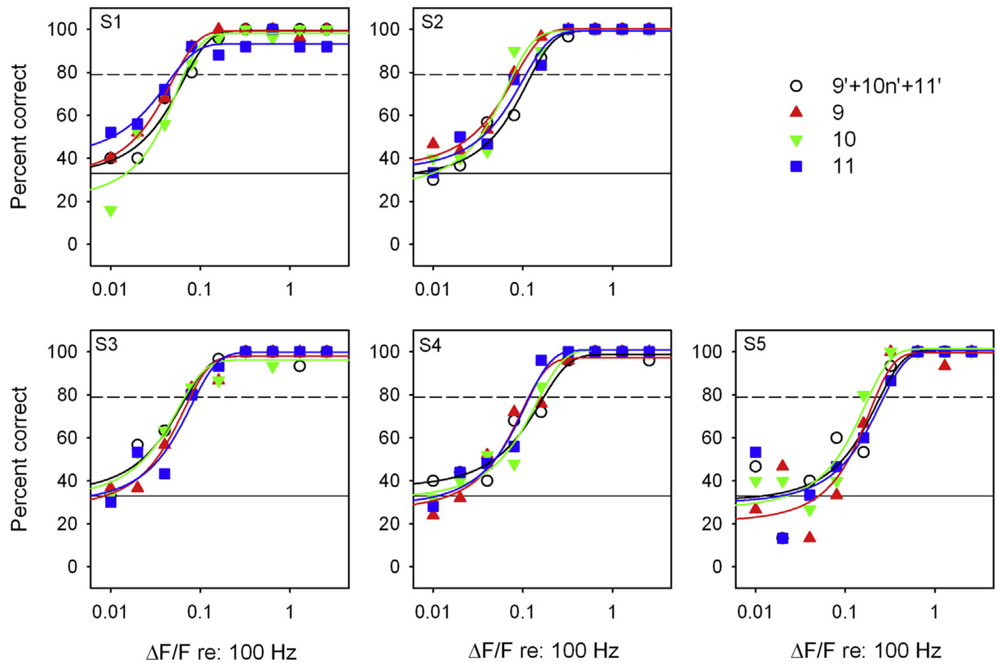

Fig. 4. AMFD for the narrow electrode configuration with similarly loud single- and multi-channel AM stimuli. Each panel shows individual subject data. The open circles show multi-channel AMDT data, and the filled upward triangles, downward triangles, and squares show single-channel data for the basal, middle, and apical electrodes, respectively. The solid lines through the data show sigmoid fits. The dashed horizontal line shows threshold (79.4% correct) and the solid horizontal line shows chance level (33.3% correct).

S1. For subjects S2 and S4, single-channel AMFD was near chance level at all modulation frequencies.

Fig. 9 shows mean percent correct across all probe modulation frequencies for the wide (left panel) and narrow combinations (right panel), for single- and multi-channel stimuli. The multi-channel data are the same as in Fig. 6. With the exception of subject S1, mean percent correct AMFD was much better with multiple than with single channels. For multi-channel AM stimuli, mean values ranged from 57% correct (S5, wide configuration) to 86% correct (S3, wide configuration). For single-channel AM stimuli, mean values ranged from 30% correct (S5, electrode 9) to 88% correct (S1, electrode 4). One-way RM ANOVAs were performed on the data shown in each panel, with stimulus (multi-channel and the three single channels) as the dependent factor and subject as the random/blocking factor. For the wide configuration, there was a significant effect of stimulus on mean AMFD [$F(3,12) = 13.1$, $p < 0.001$]. Post-hoc Bonferroni pairwise comparisons showed that AMFD with 4′ + 10w′ + 16′ was significantly better than with 4′ or 10w′ ($p < 0.05$), and significantly better with 16′ than with 4′ ($p < 0.05$). There were no significant differences among the remaining stimuli ($p > 0.05$). Because the distribution was not normal, a one-way RM ANOVA was performed on ranked data for the narrow configuration. There was a significant effect of stimulus on mean AMFD (Chi-square = 8.28 with 3 degrees of freedom, $p = 0.041$). Post-hoc pairwise comparisons (Tukey) showed that AMFD with 9′ + 10n′ + 11′ was significantly better than with 9′ ($p < 0.05$); there were no significant differences among the remaining stimuli ($p > 0.05$). A paired t-test showed no significant difference in mean multi-channel AMFD between the wide and narrow configurations ($p = 0.728$).

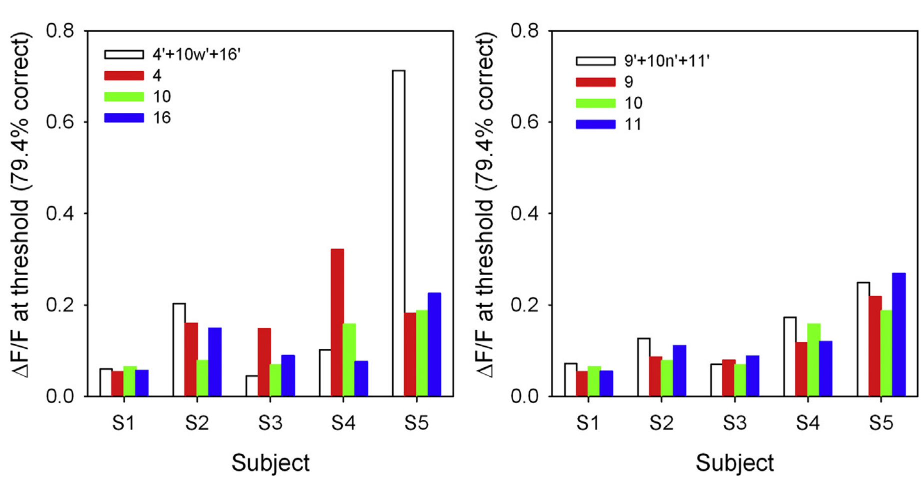

Fig. 5. ΔF/F at threshold (79.4% correct) for individual subjects, for similarly loud single- and multi-channel AM stimuli. The left panel shows the wide electrode configuration and the right panel shows the narrow electrode configuration. The open bars show multi-channel data and the filled bars show single-channel data.

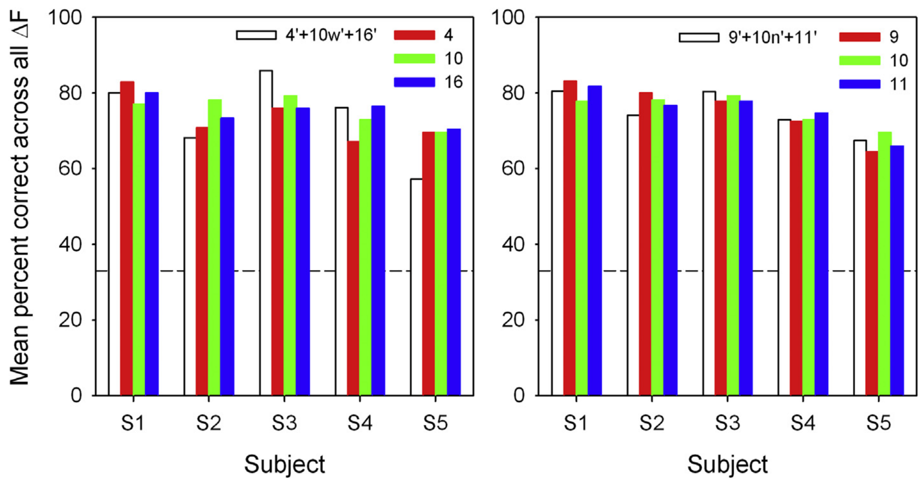

Fig. 6. Mean percent correct AMFD across all probe modulation frequencies for individual subjects, for similarly loud single- and multi-channel AM stimuli. The left panel shows the wide electrode configuration and the right panel shows the narrow electrode configuration. The open bars show multi-channel data and the filled bars show single-channel data. The dashed line shows chance performance level (33.3% correct).

4. Discussion

There was no significant effect of the distribution of component channels in the multi-channel stimuli, contrary to the hypothesis that widely spaced channels would offer an advantage over narrowly spaced channels. When single- and multi-channel AM stimuli were similarly loud, there was no significant difference in AMFD, contrary to the hypothesis that the reduced current levels needed to accommodate multi-channel loudness summation would negatively affect multi-channel AMFD. With no adjustment for multi-channel loudness summation, AMFD was better with multiple channels than with any of the component single channels, consistent with our hypothesis. Below we discuss the results in greater detail.

4.1. Effects of loudness and multi-channel summation on single-and multi-channel AMFD

In Experiment 2, AMFD was measured using the same summation-adjusted current levels and the same range of modulation (in dB) on each component channel, whether tested in the single- or multi-channel condition. Because of multi-channel loudness summation, the multi-channel AM stimuli were generally louder than the single-channel AM stimuli. AMFD was much

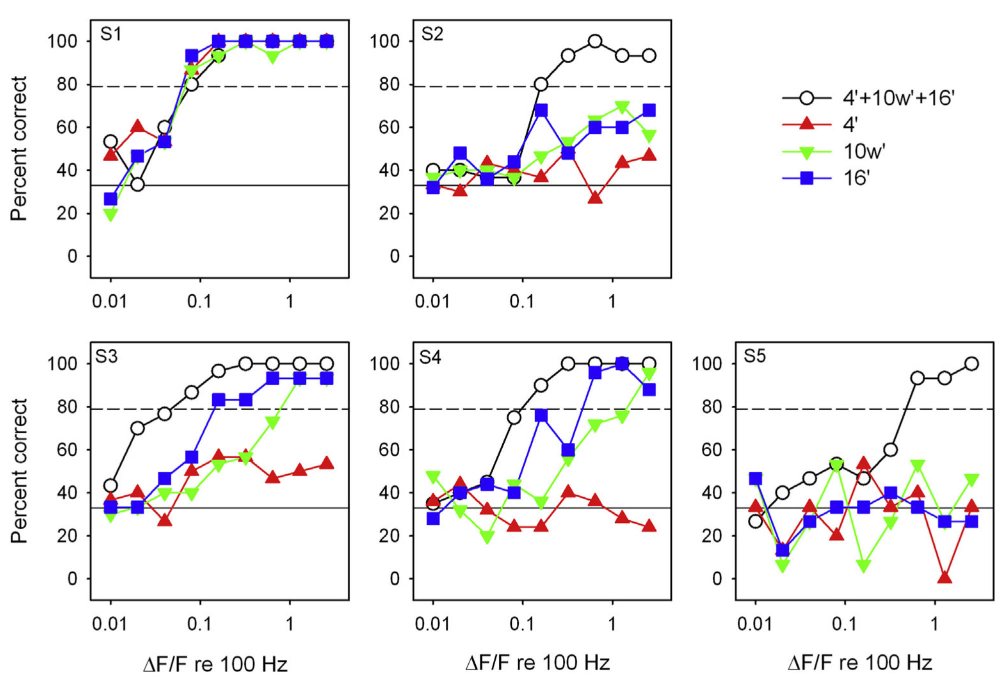

Fig. 7. AMFD for the wide electrode configuration for single- and multi-channel AM stimuli using summation-adjusted current levels. Each panel shows individual subject data. The open circles show multi-channel AMDT data, and the filled upward triangles, downward triangles, and squares show single-channel data for the basal, middle, and apical electrodes, respectively. Because there was no adjustment for multi-channel loudness summation, multi-channel AM stimuli were louder than single-channel AM stimuli. The dashed horizontal line shows threshold (79.4% correct) and the solid horizontal line shows chance level (33.3% correct).

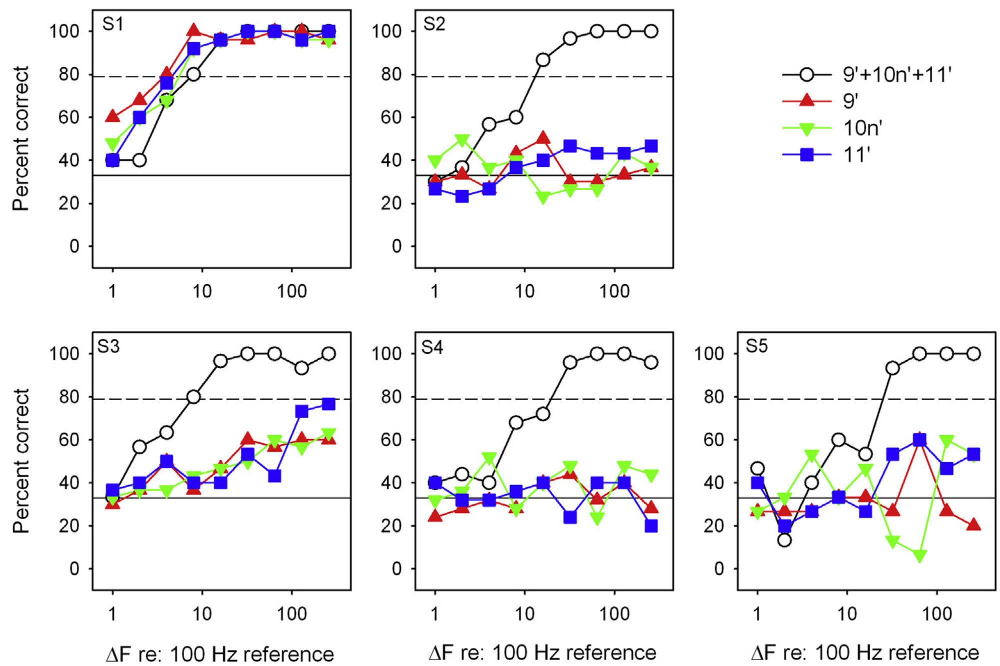

Fig. 8. AMFD for the narrow electrode configuration for single- and multi-channel AM stimuli using summation-adjusted current levels. Each panel shows individual subject data. The open circles show multi-channel AMDT data, and the filled upward triangles, downward triangles, and squares show single-channel data for the basal, middle, and apical electrodes, respectively. Because there was no adjustment for multi-channel loudness summation, multi-channel AM stimuli were louder than single-channel AM stimuli. The dashed horizontal line shows threshold (79.4% correct) and the solid horizontal line shows chance level (33.3% correct).

better with multiple channels than with any of the single component channels (see Figs. 7 and 8). This finding is in agreement with Geurts and Wouters (2001). It is unclear whether this multi-channel advantage is due to coherent envelope information delivered to multiple channels or to increased loudness. The single-channel data shown in Figs. 3 and 4 may provide some insight. When the single-channel current levels were increased to match the loudness of the multi-channel stimuli, performance greatly improved. While this difference in single-channel AMFD thresholds may be due to current level, loudness also increased with level. Combined with the multi-channel data, this suggests that loudness, which increases with current level or with the number of channels (as well as with the cumulative number of pulses), may play a strong role in AMFD, whether with single or multiple channels.

One concern with the single-channel AMFD thresholds shown in Figs. 7 and 8 is the potentially poor temporal envelope perception due to the reduced current levels. As shown in Table 2 and illustrated in Fig. 1, the minimum AM current levels for summation-adjusted single channels were lower than the original single-channel thresholds. Given these reduced reference current levels, the large AM depth may have not have been sufficient to support AMFD. As such, the perceptual range of modulation was likely much reduced for the summation adjusted single-channel AM stimuli than for the multi-channel AM stimuli. It is also possible

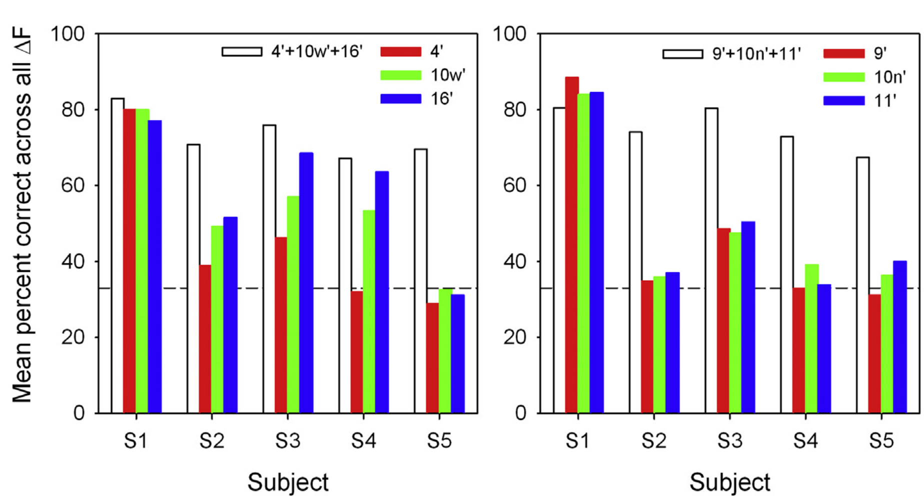

Fig. 9. Mean percent correct AMFD across all probe modulation frequencies for data shown in Figs. 7 and 8. The left panel shows the wide electrode configuration and the right panel shows the narrow electrode configuration. The open bars show multi-channel data and the filled bars show single-channel data. Because there was no adjustment for multi-channel loudness summation, multi-channel AM stimuli were louder than single-channel AM stimuli. The dashed line shows chance performance level (33.3% correct).

that the ±1 dB level roving may have been a stronger cue across intervals than differences in AM frequency, contributing to poor AMFD. Regardless of the source of poor AMFD with the summation-adjusted single channels, multi-channel loudness summation contributed strongly to the multi-channel advantage in AMFD. With any of the 3 summation-adjusted single AM channels, AMFD was often near chance level. When these channels were combined, AMFD was sharply improved. This may have been due to better perception of the AM range or to stronger perception of AM frequencies than loudness differences across intervals.

Note that subject S1 exhibited a different pattern of results than the other subjects (Figs. 7 and 8), as AMFD was similar for single- and multi-channel AM stimuli with the summation-adjusted current levels. As shown in Fig. 2, subject S1 also exhibited much less multi-channel loudness summation than the other subjects. As such, there was less current adjustment for the single-channel AM stimuli shown in Figs. 7 and 8. Consequently, single-channel AMFD was quite similar with or without the summation adjustment (i.e., the single-channel data in Fig. 3 versus Fig. 7, and Fig. 4 versus Fig. 8).

In Experiment 1, there were no significant differences among similarly loud single- and multi-channel AMFD. This highlights the importance of loudness on AMFD, rather than the distribution of envelope information in the cochlea. This finding is different from that of Geurts and Wouters (2001), who found better AMFD with multiple than with single AM channels. Several factors may contribute to these different findings. In Guerts and Wouters (2001), there was no adjustment for multi-channel loudness summation, and the modulation depth was considerably lower than in the present study. Stimuli were delivered through a research interface in the present study that allowed precise control of stimulation parameters, versus the experimental speech processors used in Guerts and Wouters (2001). Also, many more modulation frequencies were compared to the reference frequency in the present study than in Guerts and Wouters (2001), who only compared 150 Hz to 180 Hz ($\Delta F/F = 0.2$). The present data suggest no advantage in AMFD for multiple AM channels over single AM channels when AM stimuli are similarly loud, at least for the AM depth and frequencies tested.

4.2. The effect of channel distribution on multi-channel AMFD

The distribution of channels did not significantly affect multi-channel AMFD thresholds. In Guerts and Wouters (2001), three adjacent electrodes were selected for multi-channel AM stimuli, similar to the narrow spacing in the present study. The narrow configuration targeted a limited region of neurons, for which single-channel AMFD thresholds would be expected to be more similar than for the wide configuration. If multi-channel AMFD thresholds were measured at lower overall loudness levels, some effect of electrode distribution may have emerged. The present findings are also in agreement with single-channel AMFD data from Green et al. (2012), who found no significant effect of carrier pulse rate when stimuli were presented at the same percent DR (and, presumably, at similar loudness). This suggests that the total number of pulses, whether delivered to a single channel or distributed across multiple channels, did not significantly affect AMFD thresholds, provided stimuli were similarly loud.

The lack of effect for the distribution of channels is somewhat in agreement with previous multi-channel MDI CI studies. Different from the present AMFD task in which coherent modulation was delivered to multiple channels, MDI measures detection or discrimination of one modulation frequency in the presence of another modulation frequency presented to the same or different channel. The spacing between electrodes is typically varied to explore the effect of overlapping neural populations on MDI. Richardson et al. (1998) found larger MDI for narrowly spaced than for widely spaced electrodes, suggesting that multi-channel envelope processing may depend on the degree of neural overlap among channels. However, Chatterjee (2003) found no clear effect of masker-probe separation for modulation masking (i.e., the difference in MDI between a steady-state masker and an envelope masker with equivalent peak amplitudes). Chatterjee and Oba (2004) similarly found no clear effect of masker-probe separation for modulation masking. Kreft et al. (2013) found significant interference on AMFD when the masker and probe electrodes were widely separated. While the listening tasks may be different between the present and these previous studies, all seem to point toward a more centrally mediated envelope processing.

4.3. Differences between multi-channel MDT and AMFD

The present single- and multi-channel AMFD results are somewhat in contrast with previous amplitude modulation detection findings. In Galvin et al. (2014), when measured at the same loudness, multi-channel MDTs were significantly poorer than single-channel MDTs for the component electrodes used in the multi-channel stimuli. The authors argued that the reduced per-channel current levels needed to accommodate multi-channel loudness summation resulted in poorer multi-channel MDTs. Previous studies have shown that single-channel MDTs are highly level dependent, especially in the lower portion of the DR (Donaldson and Viemeister, 2000; Galvin and Fu, 2005, 2009; Pfingst et al., 2007). In this study, there was no significant difference between similarly loud single- and multi-channel AMFD thresholds, despite differences in current level between single- and multi-channel AM stimuli. Previous CI studies have shown that single-channel AMFD is level dependent (Luo et al., 2008; Kreft et al., 2010; Chatterjee and Ozerbut, 2011). The present data also showed that the mean percent correct in single-channel AMFD was better with higher current levels (Fig. 6 versus Fig. 9). Single-channel AMFD was generally poor with the lower, summation-adjusted current levels; when these channels were combined, AMFD sharply improved. The present results suggest that AMFD seems to depend more on the loudness of the stimulus (which varies with level, rate, or the number of channels), while MDT seems to depend more on the current level.

Differences in the listening task and stimuli – detecting modulation given weak envelope information (due to small AM depth and/or low presentation level) for MDT versus detecting a difference in AM frequency given strong envelope information (due to large AM depth and/or high presentation level) for AMFD – may also explain differences in the pattern of results between MDT and AMFD. Different mechanisms may also come into play for modulation detection and modulation frequency discrimination. When discriminating between AM and non-AM stimuli with the same reference amplitude, there are potential loudness cues associated with the peak amplitude of the AM stimulus (McKay and Henshall, 2010; Fraser and McKay, 2012). Given sufficient modulation depth and/or presentation level, such peak AM loudness cues do not seem to play a strong role in modulation frequency discrimination.

4.4. Limitations to the present study

In this study, a 3AFC discrimination task was used ("which interval is different?"), as in Chatterjee and Peng (2008), Chatterjee and Ozerbut (2011), Luo et al. (2008, 2010), Deroche et al. (2012, 2014). Other AMFD studies in CI users have used a 2AFC procedure (Guerts and Wouters, 2001; Green et al., 2012; Kreft et al., 2010, 2013). In the 3AFC procedure, there is no assumption of regarding the perceptual difference between the reference and probe modulation frequencies (e.g., pitch, timbre, loudness, or some other quality). These perceptual qualities may differ greatly, depending on the reference modulation frequency, as low (<50 Hz) and high frequencies (>300 Hz) may not give strong pitch percepts. In the present study, given the 100 Hz reference AM frequency (which would likely elicit a fairly strong pitch percept), AMFD thresholds may have been associated with pitch differences or some other quality, such as loudness. The loudness balancing, roving, and instructions to ignore loudness differences across intervals presumably reduced the contribution of loudness cues to the present AMFD thresholds. In Experiment 1, the range of AMFD thresholds was comparable to those found in previous studies that used a 2AFC procedure (e.g., Green et al., 2012; Kreft et al., 2010, 2013).

Loudness balancing was performed using non-AM pulse trains, rather than the AM stimuli used for AMFD. Given that current levels were swept for equal loudness at 10%, 50% and 100% DR, it seems unlikely that there would be great differences in loudness at, for example, 30% DR or 70% DR. It is possible that the loudness of AM stimuli with 100% AM depth may have differed across single channels and/or AM rates, but the effect of AM on loudness would likely be consistent across single channels. If there were indeed loudness differences across single channels when AM was applied, the current level roving (±1 dB independent level roving for each channel in the multi-channel AM stimuli; ± 1 dB global level roving for each of the 3 intervals during each trial of AMFD) helped to reduce such loudness differences.

For similarly loud single- and multi-channel AM stimuli, the overall loudness was not explicitly measured. However, subjects did not report that the AM stimuli were too soft or too loud, although the summation-adjusted single-channel AM stimuli were substantially softer. It is unclear how overall loudness might affect single- and multi-channel AMFDs, assuming sufficient envelope cues for all stimuli. Such an experiment would require sufficient modulation depth (e.g., 20% of reference amplitude, depending on the current/loudness level), but not necessarily the maximal modulation depth used in this and other studies (e.g., Kreft et al., 2010, 2013).

In Experiment 2, the poor AMFD with the summation-adjusted single-channel AM stimuli were presumably due to low current levels, which could not support AMFD even with the large AM depth used. As shown in Table 2 and Fig. 1, minimum AM current levels would likely have been inaudible. Another approach would be to use a smaller AM depth that would ensure stimulation above single-channel threshold, even after reducing current levels to accommodate multi-channel loudness summation. In such a design, it would be necessary to keep the range of modulation (in dB) constant across stimuli to examine the effects of multi-channel loudness summation on AMFD. Most likely, this approach would produce similar findings as in the present study: poor single-channel AMFD due to low current levels can be improved with multi-channel stimulation, due to the increased loudness associated with multi-channel summation.

4.5. Clinical implications

Clinical fitting of CIs must accommodate multi-channel loudness summation. The present results suggest that AMFD with multiple channels is largely unaffected by this accommodation, provided sufficient modulation depth and/or presentation levels. However, modulation detection is negatively affected by the reduced current levels needed to accommodate multi-channel loudness summation (Galvin et al., 2014). Amplification of envelope information, whether by increasing the modulation depth (envelope expansion) or by increasing current levels, may improve perception of envelope cues. There is likely to be a trade-off between amplification of envelope cues and increased noise levels for some listening environments. Selectively amplifying envelope information that is likely to be weakly represented (e.g., consonant information presented to basal electrodes) may help improve perception of envelope cues without globally increasing noise levels. The present study suggests that delivery of coherent envelope information to multiple channels may also improve perception of envelope cues, primarily due to increased loudness associated with multi-channel summation.

4.6. Conclusions

Single- and multi-channel AMFD thresholds were measured relative to 100 Hz AM in 5 CI subjects, with and without current level adjustments for multi-channel loudness summation. The electrical range of modulation was constant across AM stimuli, but the perceptual range of modulation was most likely reduced for the quieter, summation-adjusted single-channel AM stimuli. Key findings include:

1. When single- and multi-channel AM stimuli were similarly loud, there was no significant difference in AMFD thresholds. This finding is somewhat different than for modulation detection (Galvin et al., 2014), in which multi-channel MDTs were significantly poorer than those for similarly loud single channels.
2. When the same summation-adjusted current levels were used for the component channels in single- or multi-channel AM stimuli, AMFD was significantly better with multiple channels than with any of the single component channels. The poor single-channel AMFD may have been due to the lower current level, poor perception of the modulation range (which included substantial sub-audible stimulation) or to level roving (which may have obscured differences in AM frequency).
3. There was no significant effect of the distribution of electrodes for multi-channel AMFD thresholds.
4. The present results suggest that loudness, whether due to current level or the number of channels stimulated, may play a strong role in modulation frequency discrimination.

Acknowledgments

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