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Temporal Pitch Perception in Cochlear-Implant Users: Channel Independence in Apical Cochlear Regions

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Abstract

Two-electrode stimuli presented on adjacent mid-array contacts in cochlear-implant users elicit pitch percepts that are not consistent with a summation of the two temporal patterns. This indicates that low-rate temporal rate codes can be applied with considerable independence on adjacent mid-array electrodes. At issue in this study was whether a similar independence of temporal pitch cues can also be observed for more apical sites of stimulation, where temporal cues have been shown to be more reliable than place cues, in contrast to middle and basal sites. In cochlear-implant recipients with single-sided deafness implanted with long lateral-wall electrode arrays, pitch percepts were assessed by matching the pitch of dual-electrode stimuli with pure tones presented to the contralateral normal-hearing ear. The results were supported with an additional pitch-ranking experiment, in a different subject population with bilateral deafness. Unmodulated pulse trains with 100, 200, and 400 pulses per second were presented on three pairs of adjacent electrodes. Pulses were separated by the minimal interchannel delay (1.7 μs) in a short-delay configuration and by half the pulse period in a long-delay configuration. The hypothesis was that subjects would perceive a pitch corresponding to the doubled temporal pattern for the long-delay stimuli due to the summation of excitation patterns from adjacent apical electrodes, if those electrodes were to activate largely overlapping neural populations. However, we found that the mean matched acoustic pitch of the long-delay pulses was not significantly different from that of the short-delay pulses. These findings suggest that also in the apical region in long-array cochlear-implant recipients, temporal cues can be transmitted largely independently on adjacent electrodes.

Keywords

cochlear implants, apical stimulation, channel interaction, pitch matching, temporal pitch

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In modern cochlear-implant (CI) systems, sound information is encoded in spatial and temporal electrical stimulation patterns along the cochlea. In envelope coding strategies such as continuous interleaved sampling (CIS) (Wilson et al., 1991), sound information is transmitted via sequential, amplitude-modulated high-rate pulse trains. Spectral information is delivered via the tonotopic place of stimulation, and temporal information is only encoded in slow variations of the amplitude envelope. Alternative coding strategies to CIS present temporal fine structure information on low-frequency apical channels, in addition to envelope information (Lorens et al., 2010; Riss et al., 2009; Schatzer et al., 2010; Zierhofer, 2003; Zierhofer & Schatzer, 2012). Vocoder simulations with normal-hearing (NH) subjects have shown that the additional representation of temporal fine structure cues might be important for speech understanding in tonal languages for NH subjects (Xu

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& Pfingst, 2003), for localization of sounds (Smith et al., 2002), or for speech reception in fluctuating maskers (Qin & Oxenham, 2003), although it remains unclear whether acoustic temporal fine structure in NH listeners is coded via timing or tonotopic information. In CI users, tone perception in Mandarin-speaking subjects significantly improved over time with a fine structure strategy compared to CIS (Qi et al., 2017). In comparisons between fine structure and CIS coding strategies, significant improvements in long-term speech perception in noise and in quality of life (Kleine Punte et al., 2014) were found, as well as improvements in vowel and monosyllabic word understanding and strong subjective preferences for the fine structure strategy (Müller et al., 2012). In addition, spatial hearing benefits have been demonstrated with low-rate temporal fine structure cues in bilateral cochlear implant users (Churchill et al., 2014). CI users are typically able to discriminate and rank temporal information on the basis of pitch for rates of up to about 300 pulses per second (pps) (Baumann & Nobbe, 2004; Carlyon et al., 2008; McKay et al., 2000), although the intersubject variability is high and some implantees were reported to be able to discriminate rates up to 800 pps or higher (Goldsworthy & Shannon, 2014; Kong et al., 2009; Townshend et al., 1987).

A study in single-sided deaf (SSD) CI users has shown that low pitch percepts can only be elicited by applying low pulse rates on apical electrodes, more precisely on electrodes located in the second cochlear turn (Schatzer et al., 2014). Furthermore, they found that pulse rate modulations on low-frequency channels in temporal fine structure coding strategies need to be applied on second-turn electrode contacts to reproduce normal slopes of the rate-pitch functions. At shallower electrode positions, pitch increased more rapidly as a function of pulse rate than as a function of acoustic tone frequency in the tested patients. In fine structure coding strategies such as FSP or FS4 (Lorens et al., 2010; Riss et al., 2009; Schatzer et al., 2010), low-frequency information is thus represented as channel-specific low-rate temporal codes on selected apical channels.

Although CI users can discriminate well between the place of stimulation of adjacent electrodes for middle and basal stimulation sites, it has been observed that in some users, the discrimination of pitch based on purely place cues, such as provided by high-rate unmodulated pulse trains, can be poor on apical electrodes (Baumann & Nobbe, 2006; Dorman et al., 2007; Li et al., 2019). This saturation of place pitch percepts may be explained by neurophysiological properties (Hochmair et al., 2003; Spoendlin & Schrott, 1989) and the spread of the electrical field (Rattay et al., 2001a, 2001b), which may lead to an activation of largely overlapping neural populations by the most apical electrodes (Baumann & Nobbe, 2006). However, Landsberger et al. (2018) has shown that apical pitch is dominated by temporal and not place information, and Rader et al. (2016) have demonstrated that place pitch ambiguities can fully be resolved and tonotopic pitch perception restored by providing place-dependent temporal cues on apical electrodes.

In a previous study in Nucleus and Advanced Bionics CI users (Macherey & Carlyon, 2010), it was found that low-rate temporal rate codes can be applied on mid-array electrodes (typical located less than three quarters of the basal turn) with remarkable independence. Macherey and Carlyon (2010) applied dual-electrode pulse trains on adjacent electrodes in Nucleus and Advanced Bionics implant users at pulse rates ranging from 92 pps to 516 pps and asked patients to rank the pitch percepts for two different interchannel pulse train delays. In a short-delay (SD) configuration, pulses were applied in rapid succession on adjacent electrodes and in a long-delay (LD) configuration pulses were shifted by half a stimulation period between the electrodes. The hypothesis was that due to channel interaction, that is, if the same nerve fibers were activated by adjacent electrodes, patients would perceive a temporal pattern with double the frequency for the LD as compared to the SD stimulus. However, for electrode separations of 0.75 mm and 1.1 mm and with both monopolar and bipolar stimulation, the perceived pitch was on average only slightly higher for the LD than for the SD stimuli but never matched the pitch corresponding to the aggregate temporal pattern.

Spread of excitation (SoE) with electrical stimulation may be larger on apical than on middle or basal stimulation sites (Kalkman et al., 2014). The goal of this study was to investigate the effect of channel interaction, or SoE, on temporal pitch perception for unmodulated pulse trains presented on adjacent apical electrodes. Experiments were conducted for dual-electrode stimuli similar to those utilized by Macherey and Carlyon (2010), but presented on apical electrode pairs, in addition to a mid-array pair.

As was hypothesized earlier, if the pitch elicited in the LD configuration would equal the pitch with twice the pulse rate in the SD configuration, this would mean that both adjacent electrodes activate the same population of nerve fibers. Therefore, no temporal information could be transmitted independently on the two electrodes. On the other hand, an absent or smaller pitch shift would suggest a certain amount of independence of low-rate temporal cues presented on adjacent electrodes. Thus, it is important to quantitatively estimate the amount of channel interaction for temporal pitch cues, that is, to estimate how much the perceived pitch changes due to possible channel interaction. For this reason, we tested experienced SSD implant users and compared pitch percepts elicited by electrical stimulation to pitch percepts elicited by acoustic stimuli in the contralateral ear on an absolute scale (Experiment 1). At this point, it should be noted that electric to acoustic pitch comparisons can be a difficult task and that a series of strategies and checks should be implemented to be able to obtain reliable results (Carlyon et al., 2010). These are described and discussed in more detail later. To substantiate our results, we have also included data from a pitch-ranking experiment using similar stimuli, but conducted in a different subject population with bilaterally deaf CI users (Experiment 2).

The study hypothesis for both experiments is that subjects will perceive a pitch corresponding to the aggregate temporal pattern for the LD pulses as compared to the SD pulses, at least for apical pairs of electrodes. If those electrodes activated the same neurons, the aggregate pattern should lead to a pitch corresponding roughly to a doubled temporal pattern. The same is true for the middle electrode pair.

Experiment 1

Materials and Methods

Subjects. Ten adult SSD subjects participated in this study. All participating subjects were SSD implant users and part of a group who were previously studied by Távora et al., all showing benefits in noise, localization, and quality of life (Távora-Vieira & Rajan, 2014; Távora-Vieira, De Ceulaer, et al., 2015; Távora-Vieira, Marino, et al., 2015; Távora-Vieira et al., 2019). The etiologies of the ipsilateral sensorineural hearing loss and the duration of deafness varied over the subjects (Table 1). All subjects had been implanted with a MED-EL device, five were recipients of a SYNCHRONY implant, four of a CONCERTO, and one of a SONATAti100. Eight subjects were implanted with a FLEX28, one with a STANDARD, and one with a FLEX24 electrode array. All recipients have full electrode insertions, resulting in apical contacts placed well into the second turn for the FLEX28, and STANDARD arrays and below 1.5 turns for the FLEX24 array. The average age at surgery was 50.9 years (range: 18.4–70.5 years), the average duration of deafness 12.2 years (range: 0.4–41 years). The mean duration of implant use was 3.66 years (range: 0.5–9.8 years). All subjects used their implants on a regular basis and used the default frequency mapping. The pure-tone average audiometric thresholds of the nonimplanted ears had a mean of 15.6 dB hearing level (HL) (range: 6 dB–24 dB).

Electrodes. All subjects were implanted with electrode arrays that use 12 intracochlear stimulation channels. The STANDARD and FLEX28 electrodes have a contact spacing of 2.4 mm and 2.1 mm, respectively, which results in a contact span of 26.4 mm and 25.2 mm from the most apical electrode E1 to the most basal electrode E12. At full insertion, the tip of the electrode is inserted 31.5 mm into the cochlear for the STANDARD electrode and 28 mm for the FLEX28. The FLEX24 electrode has a spacing of 1.9 mm, yielding a contact extent of 20.9 mm and a full insertion length of 24 mm.

Stimuli. All presented electric stimuli were unramped, constant amplitude trains of biphasic pulses with a duration of 500 ms, which were presented on two neighboring electrodes in two different stimulation paradigms as shown in Figure 1. In the SD paradigm, the interchannel time delay between the two stimulating electrodes El A and El B was 1.7 µs, whereas in the long delay paradigm, the delay was half the period of the pulse rate. The SD and LD pulse trains were presented on three electrode pairs, the apical pairs E1/E2 and E3/E4 as well as on the middle electrode pair E6/E7. We will use a notation of the form $[A\ B]_{SD}$ and $[A\ B]_{LD}$ in the following for a stimulus on electrode pair A and B in SD or LD

Table 1. Subject Demographics.

Subject	Age at surgery (years)	Duration of deafness at surgery (years)	Etiology	Implant	Electrode	Side	PTA of the nonimplanted ear (dB HL)	Duration of implant use (years)
S1	46.9	41	Mumps	SONATAti100	Standard	Left	16	9.8
S2	70.5	3	ISSNHL	SYNCHRONY	FLEX28	Right	13	2.7
S3	18.4	0.5	Trauma	SYNCHRONY	FLEX28	Left	6	0.5
S4	65.0	30	ISSNHL	SYNCHRONY	FLEX28	Left	11	2.4
S5	53.5	0.4	ISSNHL	CONCERTO	FLEX24	Right	19	6.2
S6	40.1	34,9	Mumps	CONCERTO	FLEX28	Right	11	4.7
S7	58.3	1.5	ISSNHL	CONCERTO	FLEX28	Right	19	3.0
S8	45.0	5	Meniere	SYNCHRONY	FLEX28	Right	14	1.7
S9	65.3	2.5	ISSNHL	SYNCHRONY	FLEX28	Right	23	2.2
S10	45.6	3.5	Unknown	CONCERTO	FLEX28	Right	24	3.4

Note. PTA = pure-tone average.

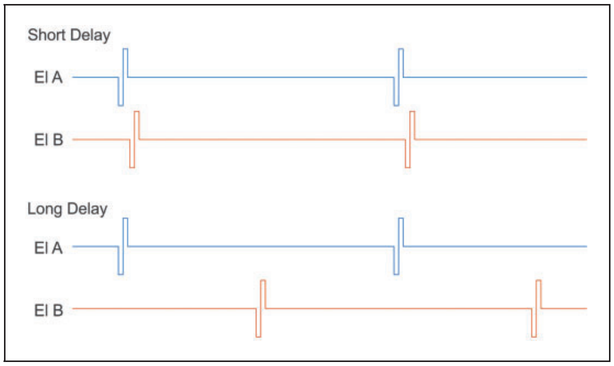

Figure 1. Dual-Electrode Stimuli as Used in the Study. In the short-delay stimulus, the temporal distance between two pulses on neighboring electrodes, El A and El B, is 1.7 µs, and for long-delay pulse sequences, the distance is half the stimulation period.

configuration. For all configurations, pulse rates of 100 pps, 200 pps, and 400 pps were used. The pulse phase durations were 47.5 µs for eight subjects, the phase durations in Subject 4 and Subject 8 had to be increased to 72.5 µs and 80.83 µs, respectively, to be able to reach comfortable loudness on some electrodes for low pulse rates.

The acoustic stimuli were pure tones with a duration of 500 ms, including linear onset and offset ramps of 25 ms duration each. The levels of all presented acoustic and electric stimuli were balanced to a comfortable loudness before pitch matching. In both loudness balancing and pitch matching experiments, pairs of stimuli were presented with a 300-ms gap. The suitability of different types of acoustic stimuli including pure tones, narrow band noise, and filtered harmonic stimuli in electric-acoustic pitch matching experiments has been analyzed in the literature (Adel et al., 2019; Carlyon et al., 2010). Adel et al. (2019) did not find differences in the variances of pitch matches for their tested stimulus types, but found that different acoustic stimulus types might lead to different pitch matches on different electrodes. For apical electrodes, they found that acoustic pure tones provided the closest pitch matches to the expected place-dependent characteristic frequencies and thus seem to be an appropriate choice for our study.

Stimulation Hardware. The Diagnostic Interface Box II (DIB II) together with a MATLAB-based software (version 9.3, The Mathworks^{TM}, Inc.) was used to determine the most comfortable loudness for each single electrode. In the loudness balancing and pitch matching procedures, electric stimuli were presented using the MAX programming interface, and the communication with the MAX interface as well as the generation of acoustic stimuli was performed with MATLAB-based software (version 9.3, The Mathworks^{TM}, Inc.). Acoustic stimuli were played through an audio interface (RME Fireface UC) and presented via circumaural headphones (AKG K 240 MK II).

Procedure

Loudness Balancing. For each subject, the loudness of the presented electric and acoustic stimuli was balanced to prevent a possible loudness induced bias on pitch perception (Arnoldner et al., 2006). First, a pure-tone acoustic stimulus was adjusted to a comfortably loud level. The frequency of this stimulus was determined by informal pitch comparisons to the intermediate electrode 4 before the actual balancing routine. Next, the electric stimulus $[3\ 4]_{LD}$ was balanced to the comfortably loud acoustic stimulus. The remaining LD pulses $[1\ 2]_{LD}$ and $[6\ 7]_{LD}$ were balanced to $[3\ 4]_{LD}$, the SD configurations were balanced to the LD configurations at the corresponding electrode pair. The chosen order of balancing aimed at minimizing the expected perceived pitch difference between two configurations within each balancing procedure. For the same reason, the balancing routine was performed for each pulse rate separately.

In the subsequently described pitch matching procedure, the frequency of the acoustic stimuli presented at the contralateral ear was adapted for each electrical pulse configuration. That means that the acoustic pure tones were played with frequencies in a range from the approximately matching lowest to highest perceived electrical pitch. This range was estimated by informal pitch comparisons to the configurations $[1\ 2]_{LD}$, $[3\ 4]_{LD}$, and $[6\ 7]_{SD}$ for each pulse rate. The loudness of the lowest, the highest, and an intermediate acoustic stimulus was then balanced to a comfortably loud electric stimulus, and the loudness of acoustic stimuli with frequencies in between is interpolated in the actual pitch matching procedure. In detail, the lowest acoustic stimulus minus half an octave was balanced to $[1\ 2]_{LD}$, the intermediate stimulus to $[3\ 4]_{LD}$, and the highest stimulus plus half an octave to $[6\ 7]_{SD}$.

A two-interval two-alternative forced-choice (2I-2AFC) paradigm was used for loudness balancing, and the subjects were asked to answer which stimulus was softer. The point of subjective equality (Dempsey) was found with a 1-up-1-down staircase procedure (Levitt, 1971). For the balancing of electric pulses, the amplitude was changed in three implant current steps until the first turning point and by one current step after that. For the acoustic stimuli, the amplitude was adapted in steps of 3 dB until the first turning point and in steps of 1 dB afterward. The procedure continued until the fifth turning point was reached, the arithmetic mean of the last four turning points was used as the balanced loudness.

Pitch Matching. The pitch matching experiments aimed at estimating acoustic pure-tone frequencies, which match the perceived electric pitches for each configuration. An interleaved adaptive procedure as proposed in (Jesteadt, 1980) and described in detail in Carlyon et al. (2010) was implemented. In this procedure, each block of trials consists of two randomly interleaved *tracks*: one following a 2-up-1-down paradigm and the other a 1-up-2-down paradigm. The two tracks converge at points where the acoustic stimulus was rated higher in pitch than the electric stimulus in 29% and 71% of trials, respectively (Jesteadt, 1980). The point of subjective equality (PSE) is then estimated as the geometric mean of these two converging points.

In a 2I-2AFC procedure, where the first interval was an electric pulse train, followed by an acoustic tone presented to the contralateral ear, the subjects were asked to answer which tone was lower in pitch. Each run with two interleaved tracks ended when both tracks had at least five turning points. The mean of the last four turning points was used as the matched pure-tone frequency for both of the tracks. The acoustic frequency was changed with a step size of four semitones until the second turning point and by two semitones afterward while the pulse rate of the electric stimuli was kept constant.

Two matching runs containing two interleaved tracks were performed for each subject and (dual-)electrode stimulus, one with an acoustic starting frequency higher (*down-matching*) and one lower (*up-matching*) than the matching electric pitch as informally estimated before the matching procedure. The starting frequencies for the up-matching and down-matching runs were randomly selected from semitone-spaced values between five and eleven semitones below and above the informally matched values. Using a starting frequency well above or below the expected target frequency can introduce a bias toward higher or lower final frequencies (Carlyon et al., 2010). To compensate for a potential bias, the final matched acoustic frequency was calculated as the geometric mean between the up-matching and down-matching tracks. This means that each obtained pitch matched acoustic frequency for a given configuration is calculated as the mean of four different runs, that is, of two interleaved 2u1d and 1ud2 tracks for each of the up- and down-matching runs. The two interleaved runs are shown for two typical examples in Figure 2. The order of the pitch matching runs was varied across subjects by randomizing the electrodes, rates, SD or LD, and the starting frequencies.

Data Analysis

Similar reliability checks as in Carlyon et al. (2010) and in Schatzer et al. (2014) were implemented in order to control for possible nonsensory biases. First, for each run, the converging frequencies f_A of the 2-up-1-down and f_B of the 1-up-2-down track were compared. The *sanity* check was passed if the f_A was less than f_B, as expected. As a second criterion, the convergence of pairs of up-matching and down-matching runs was checked. Only runs fulfilling the following condition were accepted:

$$\mathrm{abs}\left(\log_2\left(\frac{f_{\mathrm{match,down}}}{f_{\mathrm{match,up}}}\right)\right) < \mathrm{abs}\left(\log_2\left(\frac{f_{\mathrm{start,down}}}{f_{\mathrm{start,up}}}\right)\right)$$

Here, $f_{\mathrm{match,down}}$ ($f_{\mathrm{match,up}}$) denote the matched frequencies of an up (down) run (both already being the mean of the two interleaved frequencies f_A and f_B, in contrast to the corresponding equation in Schatzer et al. (2014), and $f_{\mathrm{start,up}}$ and $f_{\mathrm{start,down}}$ denote the respective starting frequencies. This means that only converging up/down pairs passed the check when the difference

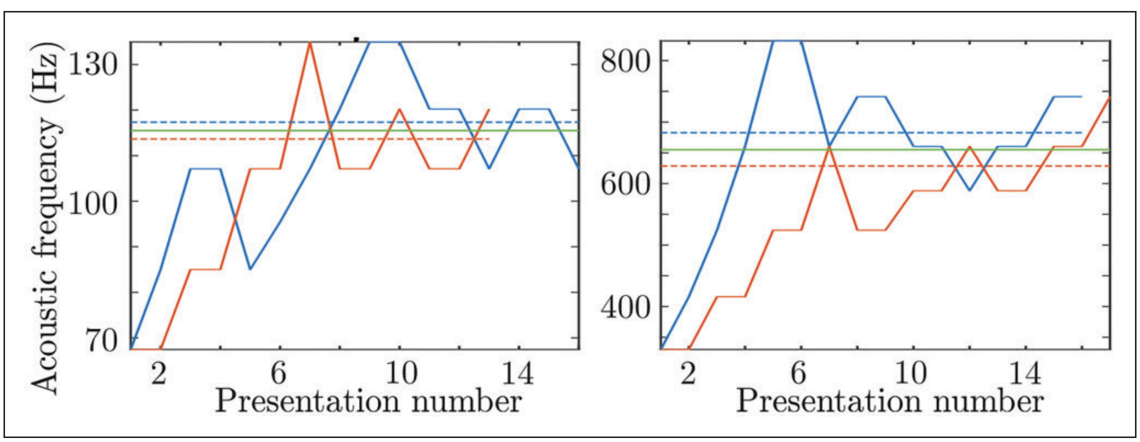

Figure 2. Typical Examples for the Interleaved Matching Procedures. Red runs: 2-up-1-down and blue runs: 1-up-2-down. The dashed red and blue lines indicate the estimates of the 71% and 29% points on the subject's psychometric function, calculated as the means of the last four turning point of the respective runs. The green line indicates the point of subjective equality, that is, the average of the 71% and 29% estimates.

of the matched frequencies in octaves was less than the octave separation of the starting frequencies. Schatzer et al. used a similar but still arbitrary criterion and only accepted pairs of up- and down-matching runs which were separated by less than half an octave separation in starting frequencies in their matching procedure. This criterion helps to avoid including obviously unreasonable results which would also lead to an increase of variability in the results.

Results

To quantitatively investigate the effect of channel interaction on temporal pitch perception, the electric-acoustic pitch matching results are presented and evaluated statistically. The pitch matching data for individual subjects are shown in Figure 3. The results are plotted for all analyzed configurations, that is, for the apical electrode pairs [1 2] and [3 4], the medial pair [6 7], and for each pair at pulse rates of 100 pps, 200 pps, and 400 pps, respectively, in SD and LD configurations. In the figure, omitted symbols represent data points that did not pass the sanity criteria. In total, about 9.4% of the runs did not pass at least one of the criteria and were therefore excluded from the analysis. The expected trends that higher pulse rates and higher electrode pairs lead to higher pitch matches can be observed, with some intersubject variability.

The mean values and standard errors for the pitch matching results that passed the sanity checks are shown in Figure 4. The mean values are also explicitly given in Table 2. The mean acoustic pitch matches for LD configurations are slightly higher than the corresponding SD configurations in six out of the nine tested electrode and pulse rate combinations, as can be seen from Figure 4 and Table 2. To statistically evaluate these results, we performed a three-way repeated-measures analysis of variance. The results showed a

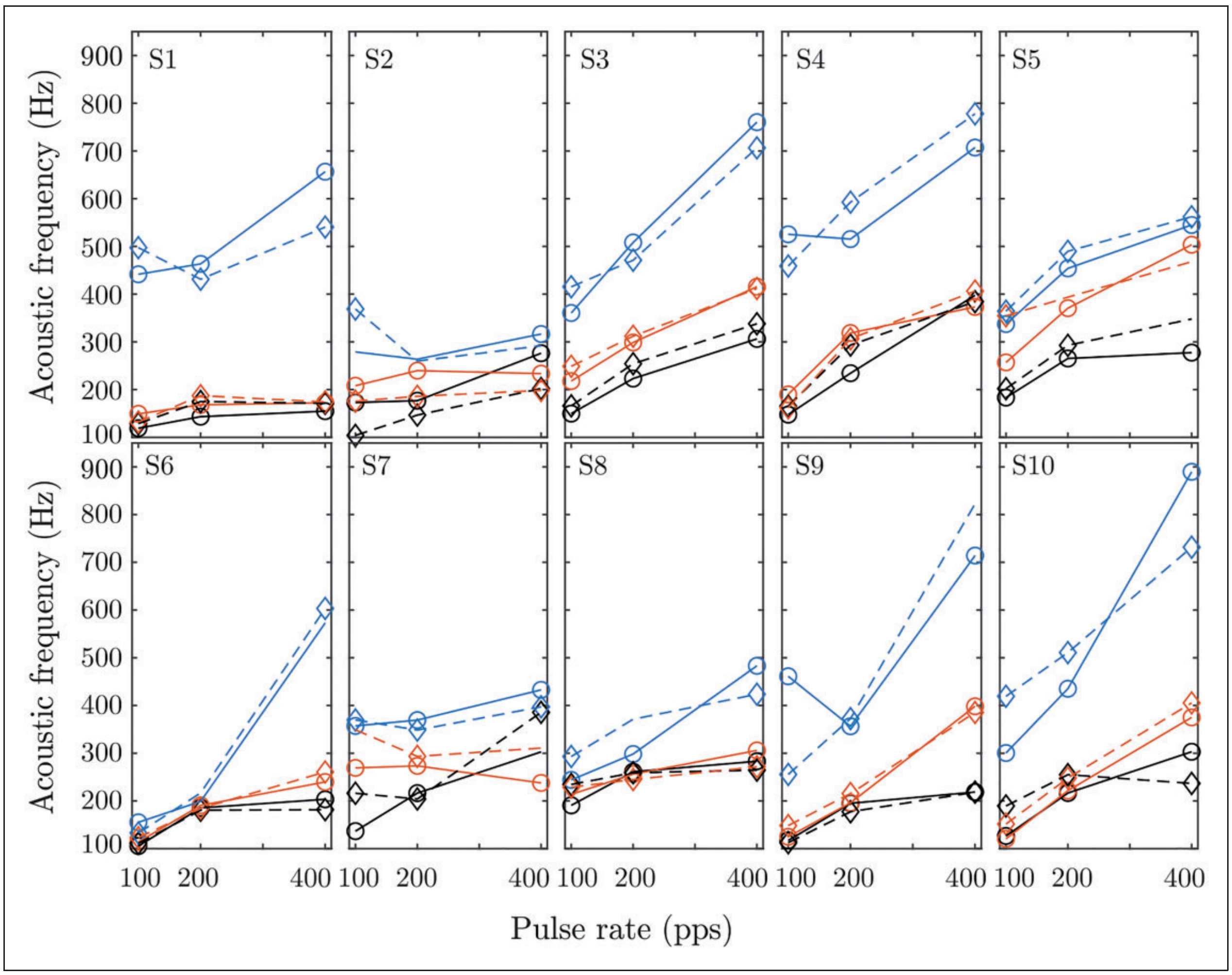

Figure 3. Individual Results for the 10 Tested Subjects. Black, red, and blue correspond to the electrode pairs [1 2], [3 4], and [6 7], circles and diamonds correspond to SD and LD configurations which are connected with solid and dashed lines, respectively. For results that did not pass the sanity checks, no circle or diamond marker is plotted.

statistically significant influence of the electrode pair—$F(2, 145) = 267$, $p < .0001$—and pulse rate—$F(2, 145) = 120$, $p < .0001$—on the perceived pitch, but no significant influence of SD or LD pulses—$F(1, 145)=0.15$, $p = .7$. No significant interactions of SD or LD pulses with rate—$F(2, 145)=0.32$, $p = .58$—or with electrode pair—$F(2, 145)=15.6$, $p = .78$—were found.

To test the hypothesis that the LD stimuli match the pitch corresponding to the aggregate temporal pattern, we also compared the LD pulses at 100 pps with the SD pulses at 200 pps and the LD pulses at 200 pps with the SD pulses at 400 pps for each electrode pair. In agreement with the results of Carlyon et al. (2010), the pitch in the LD configurations was always lower than the pitch corresponding to the aggregate temporal pattern (cf. Table 2). Paired *t* tests were performed, except for the comparison of $[3\ 4]_{LD}$ at 100 pps and $[3\ 4]_{SD}$ at 200 pps where the Shapiro–Wilk normality test failed and a signed rank test has been used instead. The results in Table 3 show that the differences are statistically significant in four out of six cases and in three out the four cases for the two apical electrode pairs.

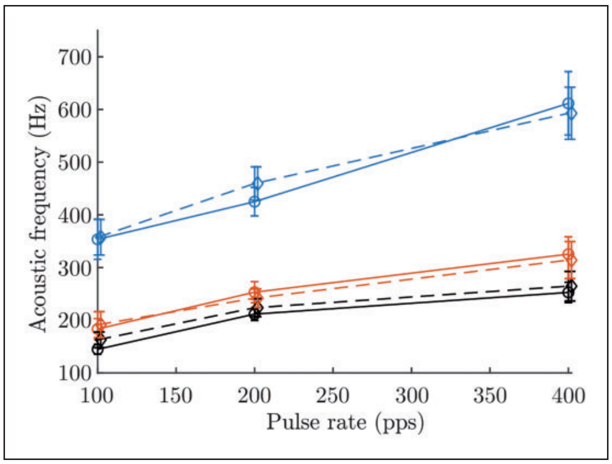

Figure 4. Mean Values for the Matched Acoustic Frequencies. Black, red, and blue correspond to the electrode pairs [1 2], [3 4], and [6 7], circles and diamonds to SD and LD configurations which are connected with solid and dashed lines, respectively. In addition, the standard errors are shown for each setting.

Experiment 2

The research question posed in Experiment 1, that is, the amount of independence of temporal cues on neighboring electrodes in the apical region of the cochlea was also investigated in traditional CI users. Bilaterally deaf CI recipients implanted with long lateral-wall electrodes performed pitch-ranking experiments for similar stimuli as in Experiment 1. The data can hence support the findings in the SSD subjects.

Materials and Methods

Subjects. The etiologies, the duration of deafness, and the duration of implant use varies over the subjects. All subjects had been implanted with a MED-EL device, four were recipients of a C40+ implant, and six of a PULSAR. These subject data are shown in Table 4.

Electrodes. All subjects were implanted with the standard electrode array, which has a length of 31.5 mm and 12 electrode contacts separated by 2.4 mm each. All

Table 2. Mean Values for the Matched Acoustic Frequencies in Hz.

el.config.	[1 2]SD	[1 2]LD	[3 4]SD	[3 4]LD	[6 7]SD	[6 7]LD
100 pps	145	162.9	183.4	191.6	353.7	357.5
200 pps	211.7	223.8	253.4	242	425.1	459.5
400 pps	252.9	264.7	325.5	314.2	611.7	592.9

Note. LD = long delay; SD = short delay.

Table 3. *p* and *t* Values for the Paired *t* Tests Comparing LD Pulse Trains at 100 pps and 200 pps With SD Pulse Trains at 200 pps and 400 pps for Each Electrode Pair.

el.	[1 2]	[1 2]	[3 4]	[3 4]	[6 7]	[6 7]
LD	100	200	100	200	100	200
SD	200	400	200	400	200	400
p	<.001	.069	.004	.028	.058	.006
t	5.33	−2.14		−2.68	−2.27	−4.49

Note. For $[3\ 4]_{LD}$ at 100 pps and $[3\ 4]_{SD}$ at 200 pps, there is no *t* value, as a signed rank test has been used. LD = long delay; SD = short delay.

recipients have full electrode insertions, resulting into apical contacts placed well into the second turn.

Stimuli. As in Experiment 1, all presented electric stimuli were unramped, constant amplitude trains of biphasic pulses with a duration of 500 ms, which were presented on two neighboring electrodes in the two stimulation paradigms shown in Figure 1. Pulse phase durations were individually chosen for each subject such that all stimuli could be presented at comfortable loudness (Table 4). The SD and LD pulse trains were presented on three electrode pairs, the apical pairs E1/E2 and E3/E4, as well as on the middle electrode pair E7/E8 for all subjects except Subject 7, where the pairs were shifted by one due to the deactivated Electrode 1. For all configurations, pulse rates 92 pps, 138 pps, 184 pps, 276 pps, 368 pps, and 552 pps were used.

Procedure

Loudness Balancing. For each subject, the loudness of the presented pulses was balanced before pitch ranking according to the following procedure. First, the more apical contact of each electrode pair was set to a comfortable loudness at a rate of 92 pps and served as a reference stimulus. After that, the two-electrode stimuli were balanced to the reference for the SD and LD configuration and all used pulse rates. To achieve this, the reference pulse and the comparison pulse were presented repeatedly in alternation with gaps of 20 ms between the stimuli. The subject could alter the loudness of the comparison pulse by pressing buttons on a screen. The subjects changed the target level until they perceived both sounds as equally loud.

Pitch Ranking. The pitch ranking procedure followed the midpoint comparison method, first described by Long et al. (2005). Within this method, every stimulus is compared one by one to a set of already ranked stimuli, until a unique position within the pitch-ranked order of the ranked stimulus set is found. The pairwise comparisons for each stimulus are selected using nested intervals, in order to minimize the number of comparisons to find this unique position. The method has several advantages, such as a low number of required comparisons and a better focus on pitch cues (Long et al., 2005; Macherey et al., 2011).

LD and SD stimuli were randomly presented at six different pulse rates in three separate blocks, that is, for the three tested electrode pairs. The procedure was repeated 10 times for each of the blocks. Balancing and pitch ranking procedures were conducted using custom-built, PC-based research software and hardware (RIB II) that was directly connected to the implant via a transmitter coil.

Results

Figure 5 presents mean pitch ranks and standard errors for the dual-electrode stimuli. Results for each of the three tested electrode pairs are analyzed with a two-way repeated-measures analyses of variance with the main factors rate and stimulus type (SD vs. LD). Similar to the results in Experiment 1, a statistically significant influence of the pulse rate on pitch rank was found for the tested pairs—[1 2]: $F(5, 45) = 57.58$, $p < .001$; [3 4]: $F(5, 45) = 37.08$, $p < .001$; and [7 8]: $F(5, 45) = 3.12$, $p < .001$. Again, no statistically significant influence of the stimulus type on the pitch rank was found for any of the electrode pairs—[1 2]: $F(1, 45) = 1.19$, $p = .3$; [3 4]: $F(1, 45) = 3.37$, $p = .1$; and [7 8]: $F(1, 45) = 0.31$, $p = .59$.

Discussion

We have investigated the effect of channel interaction on temporal pitch perception in the apical region of the cochlea. Li et al. (2019) have shown that the apical region of the cochlea is crowded with spiral ganglion neuron cells up to an angle of 720°. Although several

Table 4. Subject Demographics.

Subject	Age (years)	Etiology	Duration of deafness (years)	Duration of implant use (years)	Implant type	Pulse duration (μs)
S1	52	Unknown	38	7	PULSAR	40
S2	73	Unknown sudden	57	8	PULSAR	33
S3	54	Unknown sudden	47	3	PULSAR	37
S4	63	Unknown	39	12	C40+	33
S5	71	Unknown sudden	61	5	PULSAR	67
S6	45	Hereditary	39	3	PULSAR	30
S7	59	Trauma	43	8	PULSAR	150
S8	58	Otitis media	36	11	C40+	57
S9	18	Hereditary	6	12	C40+	58
S10	65	Unknown progressive	28	21	C40+	33

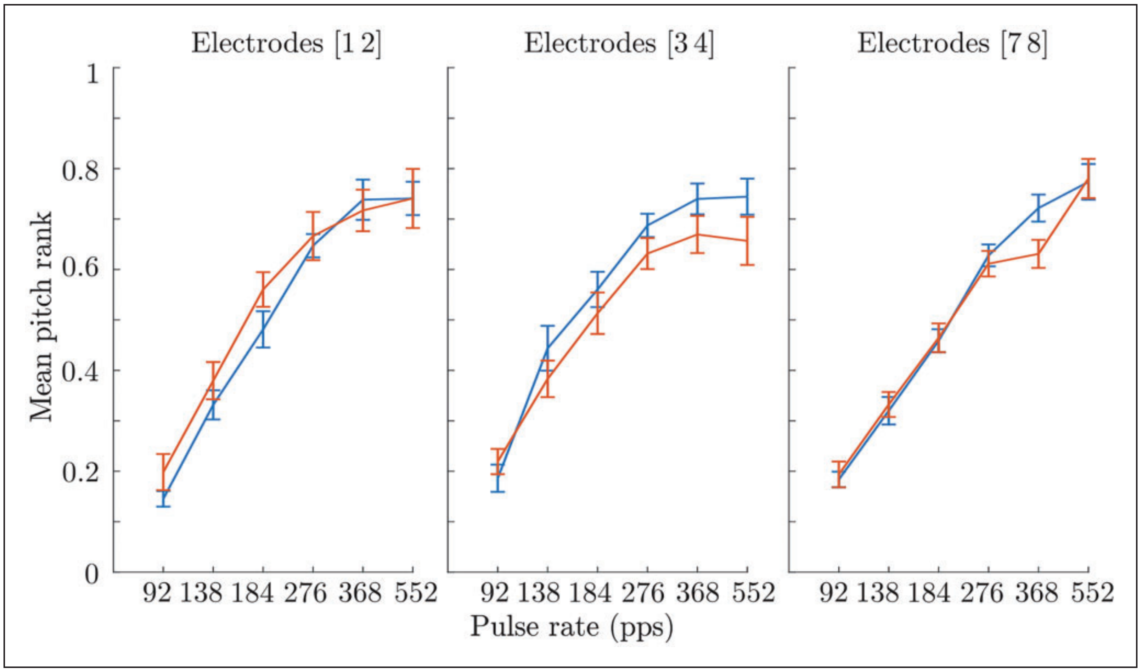

Figure 5. Pitch Ranking Results for Dual-Electrode Stimuli in Traditional CI Users (See Text for Explanation). The mean pitch ranks and standard errors are plotted against pulse rate for the three tested apical and middle electrode pairs. Results for LD stimuli are plotted in red, SD results in blue.

studies (Baumann & Nobbe, 2006; Dorman et al., 2007; Li et al., 2019) found that adjacent apical electrodes are difficult to differentiate with purely tonotopic information, the aim of this article was to specifically address whether temporal cues can be applied independently on adjacent apical electrodes.

In Experiment 1, 10 SSD MED-EL implant users, implanted with a STANDARD, FLEX28 or a FLEX24 electrode, compared pitch percepts of electric dual-electrode stimuli with acoustic pure tones perceived with the near-NH contralateral ear. Electric stimuli were unmodulated pulse trains on two apical and one mid-array electrode pair with pulse rates of 100 pps, 200 pps, and 400 pps in an SD and an LD stimulation paradigm.

We found that the pitch percepts between the SD and LD stimuli were not significantly different. Particularly, as can be seen in Figure 4, the mean pitch matches for the LD and SD stimuli are virtually overlapping. In addition, we also compared pitch matches for LD stimuli with pulse rates of 100 pps and 200 pps to matches for SD stimuli with pulse rates of 200 pps and 400 pps, respectively, for all three tested electrode pairs. Pitch matches for the LD stimuli were always lower than for the corresponding SD stimuli with doubled pulse rate and statistically significant in four out of six comparisons. This shows that contrary to the hypothesis, channel interaction is not large enough to elicit a pitch percept corresponding to the doubled aggregate temporal pattern, at least for the tested electrode spacings. Hence, the results suggest that it is possible to transmit low-frequency temporal codes largely independently even on apical electrodes, with a presumed substantial overlap of excited neural populations. This is in accordance to the findings of Macherey and Carlyon (2010) in pitch ranking experiments for mid-array dual-electrode stimuli in Advanced Bionics and Nucleus implant users. Our results also show that the mean acoustic pitch matches of the LD stimuli were somewhat higher than the corresponding SD pitch match in six out of the nine tested configurations, however, without reaching statistical significance. Macherey and Carlyon (2010) found a slightly but significantly higher pitch on average for the LD stimuli compared to the SD stimuli. The lack of a statistically significant increase in perceived pitch in our results could be due to the larger electrode spacing of 2.4 mm in our tested subjects as compared to 0.75 mm and 1.1 mm in Macherey and Carlyon (2010).

Previous studies suggested that pitch matching of electric and contralateral acoustic stimuli can be a difficult task (Adel et al., 2019; Carlyon et al., 2010; Schatzer et al., 2014). Carlyon et al. (2010) proposed the implementation of a series of checks, which strongly help to reduce possible nonsensory biases and thus reduce the variability in the results. In our study, we have tried to optimize the procedure by following these suggestions: First, we carried out a thorough loudness balancing of the used stimuli. Second, the adopted pitch matching paradigm was based on adaptive acoustic stimuli, so that no fixed range of acoustic stimuli had to be predefined. To reduce a possible influence of the starting frequency, we averaged runs with a starting frequency higher and lower than the expected matching frequency for each setting. Third, possible nonsensory biases were further reduced by using the interleaved adaptive procedure, suggested by Jesteadt (1980). In addition, possible implausible runs were discarded if they did not meet sanity criteria similar to those suggested in (Carlyon et al., 2010) and (Schatzer et al., 2014). In their work, Carlyon et al. (2010) have found very reasonable results if all these checks were implemented; in particular, they found that the pitch matchings of electric and acoustic pure tones did not deviate consistently from a widely used cochlear frequency-to-place formula or of a computational cochlear model.

Although a pitch-ranking task cannot provide results on an absolute scale, the relative pitch differences for the LD and SD stimuli can be derived from the mean pitch ranks. In agreement with previous studies (Baumann & Nobbe, 2004; Carlyon et al., 2008; McKay et al., 2000), our results in Experiment 2 showed that for both SD and LD stimuli and for all three tested electrode pairs, pitch was consistently ranked higher for increasing pulse rates, at least up to rates of about 300 pps. Most notably, no significant differences were found in the mean pitch ranks for any of the tested electrode pairs between SD and LD stimuli. This observation is consistent with the results from experiment 1 in SSD users and further supports our conclusions, as the prior results were obtained independently in a different subject population using a pitch-ranking paradigm.

A possible caveat of our testing paradigm in SSD CI listeners is that in the electric-acoustic pitch comparisons, place and temporal cues covary systematically in the acoustic ear, whereas they are changed independently in the electrical stimuli. The way a subject will match these two sounds depends on which cue they will use and how they will weight these two cues of place and temporal pitch. It is even conceivable that a listener's perceptual weighting would change from one stimulus comparison to another, further increasing the variability in the results. This however was not the case in Experiment 2 where only electric stimuli were tested. Thus, the consistency of the findings in Experiments 1 and 2 supports our conclusions based on electric-acoustic pitch comparisons in SSD CI users.

In conclusion, this study tested whether pulse trains presented on neighboring electrodes in the apical region of the cochlea would be perceived as an aggregate pitch, suggesting peripheral interactions, or independently. The lack of a perceived aggregate pitch suggests that even in the apical cochlear region, temporal information can be transmitted largely independently on neighboring electrodes, in agreement with the findings of Macherey and Carlyon (2010) from more basal cochlear regions.

Data Accessibility Statement

The raw data has been submitted alongside the manuscript.

Declaration of Conflicting Interests

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