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Verbal attribute magnitude estimates of pulse trains across electrode places and stimulation rates in cochlear implant listeners

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For cochlear implant users, temporal and place cue are assumed to vary along two orthogonal perceptual dimensions linked to pitch height and timbre. Here, the effect of electrode place, pulse rate, and amplitude modulation frequency on those perceptual dimensions was investigated. Combinations of different electrode places with differing pulse rates or modulation frequencies were presented to the participants while they were asked to rate pitch height and sound quality using multiple verbal attributes. The results indicate that temporal and place cues induce two perceptual dimensions that can be both linked to pitch and timbre.

INTRODUCTION

Pitch is one of the primary auditory sensations and plays an important role when defining and differentiating our acoustic environment. Although human listeners perform remarkably well in discriminating and ranking pitch, this task remains difficult for hearing-impaired listeners. Especially for cochlear implant (CI) users the perception of musical and voice pitch has been shown to be problematic (cf. McDermott, 2004, for a review). For normal-hearing listeners, pitch has been suggested to have multiple dimensions such as pitch height or pitch chroma. However, when dealing with the different cues that can induce a pitch-like sensation in CI users, there seems to be a lack of definition (Oxenham, 2008).

The implant can provide three different types of potential pitch cues that can be manipulated independently and that have been assumed to elicit a change in pitch height: (i) Place cues are provided by a change in place of electrode; (ii) Rate cues are associated with the pulse rate in pulses per second (pps); and (iii) Modulation cues can be provided by imposing an amplitude modulation on a sufficiently high carrier pulse train (e.g., Tong *et al.*, 1983; Shannon, 1983; McKay and Carlyon, 1999). Further, pitch can be either increased or decreased when both rate and place cues are varied in complementary or contradictory directions, respectively (Zeng, 2002). However, pitch perception remains poor in most CI users: Rate pitch deteriorates above a specific

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"upper limit" (generally 300 to 500 pps) and place cues are limited by the number of implantable electrodes, current spread, and shallow insertion depths.

Even though the sensations induced by rate cue and place cue can be ranked from low to high, they have been shown to be independent as they vary along two orthogonal perceptual dimensions (Tong *et al.*, 1983). It has been hypothesised that the dimension connected to rate may be linked to pitch height whereas the dimension connected to place may rather be linked to timbre (McDermott and McKay, 1997; McKay *et al.*, 2000). Particularly brightness, a timbre attribute associated with the spectral centroid of a sound in normal-hearing listeners, has been assumed to correlate with electrode place. Fearn and Wolfe (2000) tried to determine perceptual features other than pitch by assessing the sound quality of regular pulse trains while varying place and rate parameters. They let six CI recipients scale the pitch and sound quality for stimuli from 100 to 1000 pps presented on apical, middle, and basal bipolar electrode pairs. Results showed that low pulse rates presented on the basal electrodes were rated with the poorest sound quality and participants reported that these stimuli were rather perceived like buzzing sounds. In a similar study, Landsberger *et al.* (2016) also found ratings of the attribute "clean" to be low for low-rate stimuli presented at basal cochlear locations. Still, "cleanness" remained high when low-rate pulse trains were presented at apical locations, suggesting better sound quality when temporal code is provided apically.

It remains unclear which specific sound sensations can be linked to the physical parameters of pulse rate, place of electrode, and modulation frequency. The aim of the present study was to investigate the effect of these parameters on the perceptual dimensions associated with pitch and timbre by using verbal attributes, and to assess whether they induce independent dimensions. It was also assessed whether both changes in pulse rate and modulation frequency led to a similar patterns of results for the same timbre attributes.

METHODS

Participants

Five adult native Danish speaking participants with Nucleus devices were tested at the Technical University of Denmark (DTU). Specific participant demographics are presented in Table 1. All participants provided written informed consent and all experiments were approved by the Science-Ethics Committee for the Capital Region of Denmark (reference H-16036391). All tested electrodes were present in the participant's clinical map.

Stimuli

Stimuli consisted of single electrode, cathodic-first biphasic pulse trains. All stimuli were presented with a pulse duration of 25 μs, an interphase gap of 8 μs, and in monopolar mode. Two different sets of stimuli were generated. The first set was

Participant	Age in years	Years of implant use	Age of onset hearing loss
C1	73	13	20
C2	19	14	Birth
C3	45	2	25
C4	64	15	13
C5	43	5	Birth

Table 1: Details of the five CI users who participated in the experiment.

created by all possible combinations of electrode numbers 22, 18, 14, and 10 and pulse rates of 80, 150, 300, 600, and 1200 pps. The second stimulus set was composed of amplitude-modulated pulse trains with modulation frequencies of 80, 150, 200, 300, and 400 Hz imposed on a constant carrier of 1200 pps, presented via the same electrodes as in set 1. The amplitude of each stimulus was adjusted for presentation at a comfortable and equally loud level, as described in the following.

Procedure

The loudness growth for all stimuli was estimated before loudness balancing. On a single electrode, a stimulus was played initially below threshold and then gradually increased in 0.88-dB steps from threshold to upper comfort level. The 10-point loudness scale from Advanced Bionics was used to let the participants indicate the loudness level of each stimulus presentation. For loudness balancing, the reference stimulus was a 300-pps pulse train on electrode 18. This stimulus was first adjusted to have the most comfortable level. Thereafter, pulse trains of the same rate but differing in electrode number were balanced to this reference. For this, two stimuli were presented with a duration of 500 ms and with a 500-ms interstimulus interval at amplitudes corresponding to what had been previously described as the most comfortable loudness in the first interval, and a lower loudness level in the second. After participants adjusted the loudness of the test stimulus to be the same of the reference, both reference and test stimulus were swapped and the test stimulus was presented at the previously determined comfort level in the first interval while the reference was balanced to it. The adjusted level was calculated by averaging the current difference in the logarithmic domain. Once the 300-pps pulse trains were set to equal loudness, the 80-pps, 150-pps, 600-pps, and 1200-pps pulse trains were each balanced to the 300-pps pulse train on the same electrode.

After loudness balancing, participants were familiarised to the range of stimuli and definitions and descriptions for all attributes were provided in Danish, taken from the DELTA lexicon of sound-describing words (Pedersen, 2008). The listeners were then presented with one randomly selected single electrode pulse train with a duration of 2 s and asked to rate "pitch height", as well as sound quality, using multiple verbal attributes, i.e., "calm", "loud", "clean", "complex", "bright", "lively", "rough", "boomy", and "humming" which were translated into Danish (i.e., "høj", "rolig", "kraftig", "ren", "kompleks", "lys", "livlig", "ru", "dybtoneresonant", "summende"). Responses were collected on continuous verbal attribute magnitude estimate scales ranging from 0 to 100, with 100 translating into a full agreement between the attribute and the sound specific sensation and 0 to the opposite. All attributes were displayed at the screen at the same time and in random order. In a single trial, participants could click on a "play" button to be presented with the stimulus and were encouraged to repeat the sounds as often as necessary. The procedure was repeated until 3 measurements were collected for each stimulus with each of the ten descriptors for all participants.

To reduce variability and investigate the relationship between the physical parameters and pitch height, brightness, and roughness further, five more repetitions were conducted for these attributes with the same participants.

RESULTS

Results in Fig. 1 show the principal component analysis (PCA) for scalings of all 10 attributes with variables plot (left), scores plot (right) for stimulus set 1 (top) and stimulus set 2 (bottom). The number of dimensions kept in the results was estimated by using the generalised cross-validation approximation method. The data are scaled to unit variance.

The scores plot for stimulus set 1 seen in Fig. 1 (upper right) shows that the first two principal components can account for around 80% of the variance. For stimulus set 2 (Fig. 1, bottom right), approximately 70% of the variance can be explained by components 1 and 2.

The variables plot for both stimulus sets (Fig. 1, left panels) shows that many of the chosen attributes covary. However, the majority of the attributes lies orthogonal to the attribute pitch height, e.g., roughness, complexity, cleanness, calmness, etc. As all attributes were supposed to be equated in loudness, the attribute loud is only showing weak correlation with low-rate pulse trains on apical electrodes. Brightness, which has previously been associated with place of excitation, does neither show the same ratings as pitch height, nor is orthogonal to it.

Results from the repeated measurements on pitch height, brightness, and roughness are shown in Fig. 2 and Fig. 3. The results are analysed by means of a mixed model with two within-listener factors, pulse rate and electrode place, and the random effect participant.

Scalings for pitch height, as seen in Fig. 2 (left), were in agreement with previous findings showing a significant dependency of pitch on electrode place [$F(3,4) = 31.24, p < 0.005$] and pulse rate [$F(4,4) = 33.80, p < 0.005$] (e.g., Fearn and Wolfe, 2000; Landsberger *et al.*, 2016), while showing no significant interaction effect. For roughness (Fig. 2, middle), participant was a significant random effect ($p < 0.005$) too and pulse rate was a significant main factor [$F(4,4) = 34.77, p < 0.005$]. However, post-hoc paired t-tests with Bonferroni adjustments indicated no significant difference

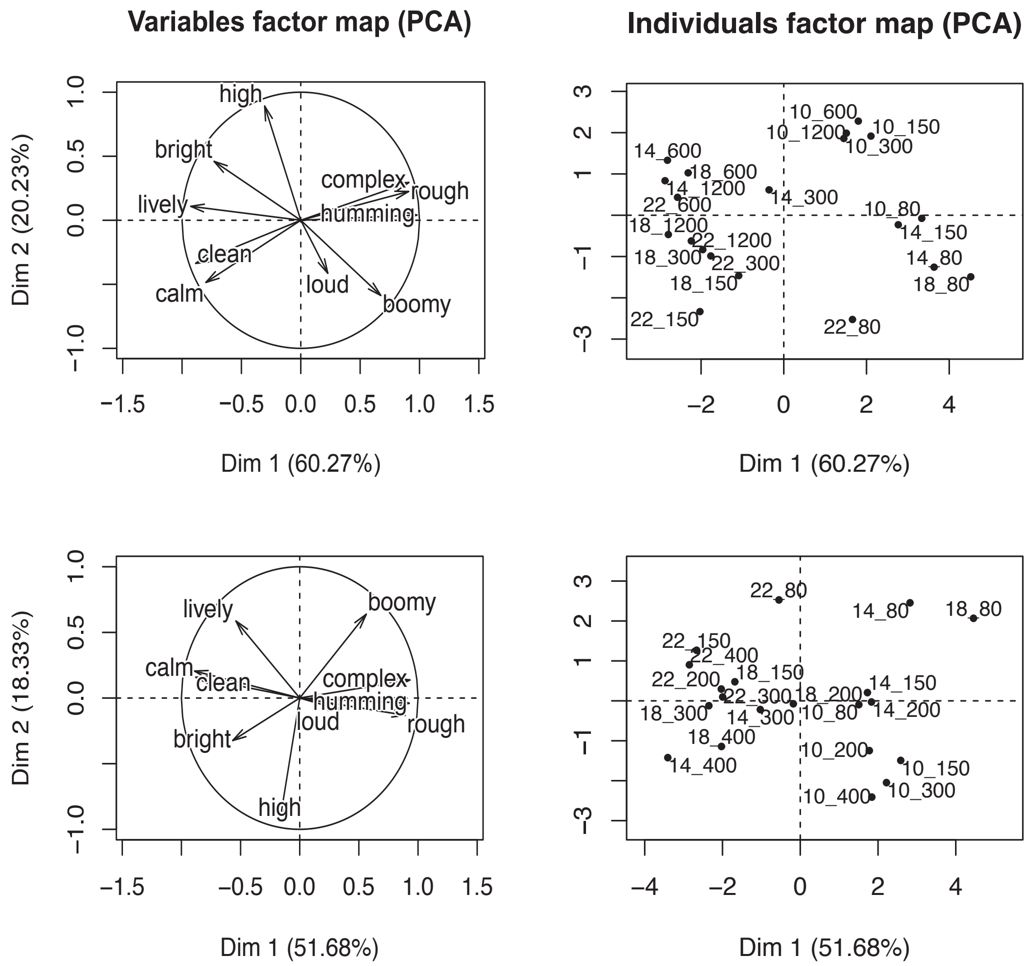

Fig. 1: Variable (left) and scores plot (right) of a principal component analysis for the ten attributes used in the experiment. Top and bottom show results for stimulus set 1 and 2, respectively. The scores plot shows electrode numbers followed by pulse rate.

for rates above 600 pps. Electrode place showed a non-significant tendency of low-rate pulse trains being rated as less rough when presented at apical cochlear locations than at basal locations [$F(3,4) = 1.06, p = 0.37$]. For brightness (Fig. 2, right), pulse rate [$F(4,4) = 36.19, p < 0.005$] and electrode place [$F(4,4) = 12.33, p < 0.005$] were significant main effects. Interestingly, brightness was the only attribute for which there was a significant interaction between the two main factors [$F(4,4) = 3.8, p < 0.05$].

Figure 3 shows scalings for modulated pulse trains (stimulus set 2). For pitch height, rate [$F(4,4) = 36.28, p < 0.005$], electrode place [$F(3,4) = 15.33, p < 0.005$], and participant ($p < 0.05$) were significant. For roughness, the effects of rate [$F(4,4) = 33.42, p < 0.005$] and electrode [$F(3,4) = 11.20, p < 0.005$] were significant. For

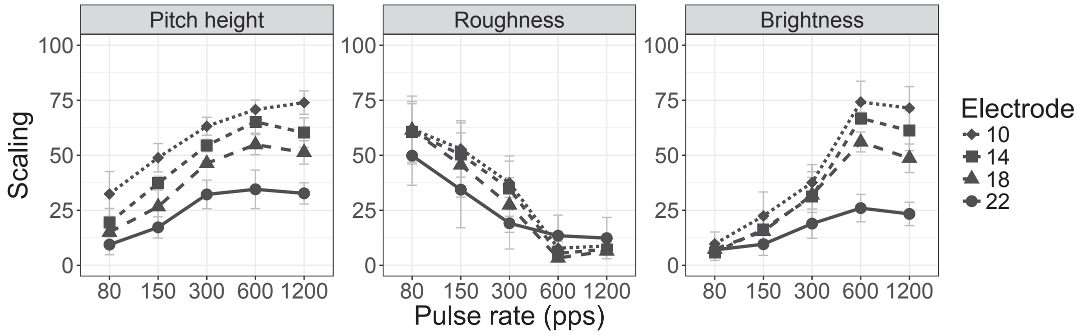

Fig. 2: Average of scaled values for all participants for pitch height (left), roughness (middle), and brightness (right) for unmodulated pulse trains. Electrode 22 is the most apical electrode in the Cochlear device. Error bars depict the standard error.

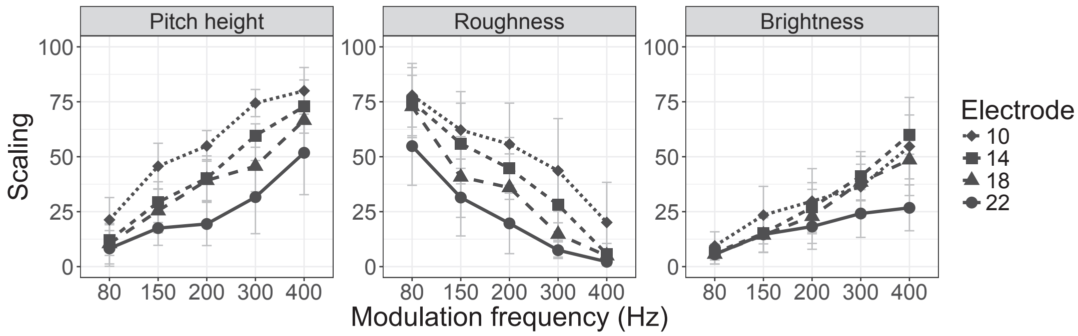

Fig. 3: Average of scaled values for all participants for pitch height (left), roughness (middle), and brightness (right) for modulated pulse trains on a constant carrier rate of 1200 pps. Error bars depict the standard error.

brightness, rate [$F(4,4) = 25.78, p < 0.005$], electrode [$F(3,4) = 4.44, p < 0.05$], and participant ($p < 0.005$) were significant effects as well. However, for the brightness attribute only scalings on electrode 22 differed significantly from those for other electrodes. No significant interaction effect was found for any attribute using stimulus set 2.

Stimulus set 1 and 2 showed very similar results: There was no significant difference in scalings between the results of these two sets for frequencies of 80, 150, and 300 Hz, and pulse rates of 80, 150, and 300 pps. The only attribute for which a significant difference between stimulus sets emerge, was roughness [$F(1,4) = 7.63, p < 0.05$].

DISCUSSION

The results of the PCA showed that most of the variance in the data set could be explained by the first two principle components. Further, first and second principal components seemed to be related to the pulse rate and electrode place, respectively. The majority of attributes lay orthogonally to pitch height, e.g., roughness or cleanness, which may be connected to sound quality or pleasantness. The lack of correlation between pitch height and roughness suggests that different rate and place combinations may induce similar pitch-like sensations but that their sound qualities might differ substantially. Scalings for brightness lay in-between these two dimensions, suggesting a combined effect along the first two principal components.

Scalings for pitch height were consistent with previous literature (e.g., Fearn and Wolfe, 2000) as they show the expected changes with pulse rate and electrode place. Roughness, as a possible indicator for sound quality, showed less dependency on electrode place than in previous results, (e.g., “cleanness”, Landsberger *et al.*, 2016), despite a non-significant trend in the scalings. The smaller number of participants in the present study compared to Landsberger *et al.* (2016) may explain the lack of significance. Further, this trend was significant for the amplitude modulated pulse trains in stimulus set 2. Lower scalings for roughness on low-rate apical pulse trains may be linked to the idea of a better place-rate match for this type of stimulation (Oxenham *et al.*, 2004). Apart from better sound quality at apical cochlear regions, other studies, such as Macherey *et al.* (2011) and Stahl *et al.* (2016), also suggested that temporal processing could be improved when provided apically. They found a significantly higher upper limit and lower rate discrimination thresholds at the apex relative to more basal cochlear locations. These results suggest that temporal coding, i.e., rate pitch, is likely be conveyed more pleasantly but also more adequately when provided apically. Finally, scalings for most attributes did not reveal a significant interaction effect, as shown before (see McKay *et al.*, 2000). However, it is interesting to note that this is not the case for the attribute brightness. It seems that differences in brightness scalings emerged only for high rates where a change in the temporal code no longer evokes a change in perceived pitch and only place of excitation cues are available.

Similar results were obtained for stimulus set 1 and 2. This may indicate similarities in sound quality and seems consistent with measures of temporal acuity in CI listeners. Kong *et al.* (2009) showed that rate discrimination thresholds have similar patterns for both modulated and unmodulated pulse trains, indicating a similar pitch salience for these stimuli.

CONCLUSION

The statistical analysis revealed no significant interaction effect between temporal and place cues, apart for scalings for the attribute brightness. This may suggest that the two cues are not totally independent, at least when scaling this particular attribute. A comparison between scalings for modulated and unmodulated pulse trains only showed a significant difference between the two sets for the attribute roughness. Results suggest that neither pitch nor timbre exclusively covary with electrode place, pulse rate, or modulation frequency.

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