Research Paper

Perception and prediction of loudness in sound coding strategies using simultaneous electric stimulation

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A B S T R A C T

Cochlear Implant (CI) sound coding strategies based on simultaneous stimulation lead to an increased loudness percept when compared to sequential stimulation using the same current levels. This is due to loudness summation as a result of channel interactions. Studying the loudness perception evoked by dual-channels compared to single-channels can be useful to optimize sound coding strategies that use simultaneous current pulses. Fourteen users of HiRes90k implants and one user of a CI implant loudness balanced single-channel to dual-channel stimuli with varying distance between simultaneous channels. In this study each component of a dual channel was a virtual channel, which shared current across two adjacent electrodes. Balancing was performed at threshold and comfortable level, for two spatial references (apical and basal) and for dual-channels with different relative current ratios. Increasing distance between dual-channels decreased the amount of current compensation in the dual-channel required to reach equal loudness to a single channel component by an average of 0.24 dB/mm without a significant difference between threshold and most comfortable level. If the components of the dual-channels were not at equal loudness, the loudness summation was reduced with respect to the equal loudness case. The results were incorporated into an existing loudness model by McKay et al. (2003). The predictions from the adapted model were evaluated by comparing the loudness evoked by simultaneous and sequential sound coding strategies. The application of the adapted model resulted in a deviation between predicted and actual behavioral loudness balancing adjustments in electrical level between simultaneous and sequential processing strategies of 0.24 dB on average.

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1. Introduction

The sound coding strategy of the cochlear implant (CI) can be used to control the trade-off between speech performance and power consumption. Most commercial CI strategies stimulate only one electrode at a time. One can add simultaneous stimulating channels such that the electrical interaction between channels is increased and obtain power savings. It is known that simultaneous electric stimulation produces a louder sound percept than sequential electrode stimulation when both have the same amplitude due to the overlap of the two current fields and the loudness summation in that area of overlap (Frijns et al., 2009; Marozeau et al., 2015; Snel-Bongers et al., 2013). This study investigated loudness perception of simultaneous electric stimulation with different stimulus configurations, using virtual channels.

Some current developments in sound coding strategies for CIs focus on power consumption reduction by using simultaneous stimulation. For instance, virtual channels or current steering is a technique that was developed to increase the number of stimulation sites in the cochlea, lower the compliance limit and reduce the maximum peak current (the highest current amplitude across electrodes). In current steering, two adjacent electrodes are stimulated simultaneously with weights α and 1−α to shift the locus of the electric excitation between two physical electrodes. The original virtual channel sound coding strategy Fidelity 120 by Advanced Bionics used an α coefficient ranging from 0 to 1, however, the recently released Optima sound coding strategy restricted this range between 0.25 and 0.75 to make sure that always two electrodes are stimulated simultaneously to save power.

Another possibility to obtain further power savings is to stimulate with pairs of virtual channels (called dual-channels hence-
forth), such as in the Optima-Paired sound coding strategy. A sound coding strategy that stimulates with dual-channels resulted in similar speech-in-noise performance and spectral modulation detection thresholds but a reduction in power consumption of 20% on average when compared to a strategy with only one virtual channel (Langner et al., 2017). However, it remains unclear how loudness from such dual-channels is influenced by different stimulus configuration parameters such as distance or current ratio between dual-channels. Characterizing electrical interactions of dual-channels will provide information that may be useful to control loudness in such strategies. This study investigated loudness perception for dual-channel stimulation with different psycho-physical loudness comparisons using single-channel stimulation as a reference. Insights from this study were applied to a state-of-the-art loudness model for electric stimulation to predict loudness for simultaneous stimulation. With the adaptation, switching sequentially and simultaneously stimulating strategies in clinical practice without necessitating additional behavioral measurements could be made possible.

Loudness is a measure that describes how intensely a sound is perceived by a listener. For a CI listener, loudness is influenced in general by the interaction of stimulating electrodes/channels on a temporal and spatial basis (Shannon, 1983). Loudness is also affected by the amount of loudness summation which among many factors depends on whether the stimulus pulses are presented sequentially or simultaneously. It has been shown that for simultaneous electrode stimulation, a smaller distance between two electrodes results in a larger area of overlap between the two current fields which in turn leads to greater loudness summation and a stronger loudness percept when compared to sequential stimulation of the same electrodes with the same current amplitude (White et al., 1984). Tang et al. (2011) assessed threshold detection and loudness summation in response to simultaneous in-phase and out-of-phase stimulation, but did so with dual-electrodes and low rates of 100 Hz. They concluded that loudness summation did not occur at threshold for the highest distance between dual-electrodes but it did occur at supra-threshold levels. The present study will focus on a more practical approach by performing loudness balancing at rates of around 1000 Hz with dual-channels which are used in commercial sound coding strategies. Additionally, the definition of electric interaction is different between the one described in Tang et al. (2011) and ours: Tang et al. define the interaction in the perceptual part as a method of measuring the direct electrical summation, contrary to our loudness summation which would occur even if the electric fields did not overlap. Marozeau et al. (2015) investigated average current level differences between sequential and simultaneous stimulation when adjusted to a similar loudness with the monopolar stimulation mode. Their results with five CI users showed level differences of 4 dB on average for the smallest distance of around 1 mm and that the level difference decreased with increasing distance of up to 5 mm between the simultaneously stimulating electrodes. Our study compared the loudness of dual-channels to that of single virtual channels and will extend the range of distance between dual-channels to span the entire electrode array (up to 11 mm).

Another parameter that influences loudness perception is the current ratio between simultaneously stimulated electrodes/channels. Increasing the difference in current between channels (making the channels more unbalanced) will result in a smaller overlap of the current fields which results in less loudness summation with respect to more balanced channels. Decreasing current of one channel continuously, the dual-channel would eventually become more similar in loudness to a single channel. This information is needed because in sound coding strategies based on simultaneous stimulation, the dual-channels are rarely activated with equal current. To investigate the effect of current ratio on loudness, different ratios were applied on the dual-channel stimuli and loudness differences were quantified with respect to a single-channel stimulus.

In this study, the “practical method” to predict the loudness of complex electric stimuli developed by McKay et al. (2003) and the extension for dynamic stimuli by Francart et al. (2014) were used to predict loudness for simultaneous electric stimulation. McKay et al. developed the method based on their earlier loudness model (McKay et al., 2001) with a simplifying approximation. The approximation stated that every single pulse in a fixed time interval contributes independently to the predicted loudness, because the effects of electrode distance on refractoriness and channel interaction compensate with each other on average for sequential pulses. In the model, the total predicted loudness is the sum of all loudness contributions from each pulse located in a temporal integration window. Francart et al. (2014) introduced an extension for time-varying stimuli to investigate loudness of various signals using electric stimulation and consequently predict loudness for different sound coding strategies. Various modulated pulse train stimuli with adjustable pulse rates were loudness balanced to a reference stimulus. Francart et al. (2014) used the output from the McKay et al. (2003) as the input instantaneous loudness for the time-varying loudness (TVL) model of Glasberg & Moore (2002). In the TVL model, instantaneous loudness was converted via temporal integration by a recursive first order low pass filter to short-term loudness (attack and release time of 22 and 50 ms, respectively) and short-term loudness in the same way to long-term loudness (10 and 0.5 ms). The percept of loudness that CI users report is the predicted long-term loudness. Neither of these methods have been designed to account for loudness of simultaneous dual-channels. Note that Frijns et al. (2009) and Nogueira et al. (2017) have created models of simultaneous electrode stimulation, but not dual virtual-channel stimulation. Although both of these models could be adapted for this kind of stimulation, the McKay practical method is more time efficient and simpler to predict loudness from sound coding strategies than the more physiologically oriented models as the ones by Frijns et al. (2009) and Nogueira et al. (2017). To apply this model to dual-channel stimulation, the psychophysical results in the study were used to define hypothetical single pulses (summed current from each electrode of a channel) with equivalent loudness to each simultaneous dual-pulse.

Summarizing, this prospective study quantified the known effects of distance and current ratio for the stimulus paradigm of simultaneous virtual channels and applied the McKay model to predict loudness for simultaneous stimulation. It further evaluated the accuracy of predictions of the model for loudness of sound processor outputs. The adapted model presented here has been made publically available in a GitHub repository (Langner et al., 2020).

2. Methods
2.1. Subjects

Subjects were fifteen postlingually deafened adults. Specific demographics are reported in Table 1. Inclusion criteria consisted of one year of CI experience and a minimum of 18 years of age. Fourteen were users of the Advanced Bionics HiRes90k implant. Ten had a Helix and four a Mid-Scala electrode array. One subject had a Clarion CI implant and a 1j electrode array. Note that there is a difference in electrode distance between the Helix (0.85 mm) and Mid-Scala/1 J (0.975 mm) arrays, which will be later addressed in the analysis of the results. Participants were offered regular breaks and were free to pause at any time during the experiments. All participants gave written consent prior to the experi-


Table 1

Demographic details of all participating CI listeners.

| ID   | Age (yrs) | Gender | etiology      | Duration of deafness (yrs) | CI usage (yrs) | Array type |
|------|-----------|--------|---------------|----------------------------|----------------|------------|
| CI01 | 62        | m      | unknown       | 1                          | 4              | Mid-Scala  |
| CI02 | 69        | f      | acute         | 0                          | 7              | Helix      |
| CI03 | 20        | m      | unknown       | 0                          | 6              | Mid-Scala  |
| CI04 | 59        | f      | acute         | –                          | 6              | Helix      |
| CI05 | 53        | f      | hereditary    | 5                          | 16             | Helix      |
| CI06 | 47        | f      | unknown       | 10                         | 5.5            | Helix      |
| CI07 | 23        | f      | unknown       | 8                          | 10             | Helix      |
| CI08 | 52        | m      | Meniere       | 2                          | 5              | Helix      |
| CI09 | 74        | m      | acute         | 6                          | 9              | Helix      |
| CI10 | 60        | m      | unknown       | 3                          | 11             | Helix      |
| CI11 | 70        | m      | acute         | 0                          | 5              | Mid-Scala  |
| CI12 | 66        | f      | genetic       | 0                          | 10             | Helix      |
| CI13 | 68        | f      | acute         | 1                          | 6              | Mid-Scala  |
| CI14 | 53        | m      | acute         | 4                          | 17             | 1j         |
| CI15 | 61        | f      | genetic       | 0                          | 10             | Helix      |

Fig. 1. Example of the loudness balancing procedure and CC calculation with reference to Eq. (1). Channel distance is denoted by d.

2.2. Stimuli

The electric stimuli used in the study were presented directly to the implant via transmitter coil from a Platinum Sound Processor connected to HRStream and a standard PC. HRStream is a research interface from Advanced Bionics for electrical stimulation of the auditory nerve with HiRes90k or CI1 implants, that has been used in previous studies (Carlyon et al., 2014; Nogueira et al., 2017; Nogueira and Büchner, 2012; Srinivasan et al., 2013). All experiments and conditions used virtual channels, which are standard in the clinical sound coding strategies for this implant and are assumed to be similar to single electrode stimulation with regards to the effective voltage spread in the cochlea (see Fig. 1 in Langner et al. (2017) and Bonham & Litvak (2008) as well as Busby et al. (2008)). The virtual channels were composed of two adjacent simultaneously-activated electrodes with a fixed steering factor $\alpha = 0.5$. Pulse trains were composed of biphasic cathodic-first pulses with 50 $\mu$s phase duration, no interphase gap and a rate of 946 pps. This phase duration was the longest in use across the clinical speech processors of all subjects hence this choice guaranteed a loud enough percept across all participants within compliance limits. The implant casing was used as the return electrode (monopolar). All stimuli had a duration of 1000 ms. In all of the psychophysical tasks, pauses between each stimulus presentation were 500 ms long. Dual-channel stimuli consisted of two simultaneously activated virtual channels. Single-channel stimulation is denoted $W_X$, with $W$ as the first and $X$ as the second electrode in the virtual channel. Dual-channel stimulation is denoted by $[W_X, Y_Z]$, with $W_X$ as the first and $Y_Z$ as the second virtual channel. Current ratios ($r$) in experiment 3 are defined as the amount of current reduction in percent of dynamic range of the second dual-channel.

2.3. Experiment 1: Loudness balancing between single and dual-channel stimuli at MCL

To investigate the effect of the distance between simultaneously stimulating channels on loudness perception, ten participants (namely CI01 to 03, 05 to 09, 11 and 13) performed two tasks during the experiment. In each of these tasks, the participant used a rotational controller with no anchor to adjust the loudness (effec-
Table 2
Principle of the two spatial references to investigate the effect of spatial location and electrode distance along the electrode array. Numbers indicate stimulating electrodes (e.g., 3, 4 for electrodes 3 and 4 as one current steered channel).

| Spatial reference | Target Signal | Spatial reference | Target Signal |
|-------------------|---------------|-------------------|---------------|
| Apical 1, 2, 3, 4 | 1, 2 | Basal 1, 2 | 15, 16 |
| Apical 1, 2, 4, 5 | 2, 3 | Basal 1, 2 | 15, 16 |
| Apical 1, 2, 5, 6 | 1, 6 | Basal 1, 2 | 15, 16 |
| Apical 1, 2, 3, 4, 5, 6 | 1, 2, 3, 4, 5, 6 | Basal 1, 2 | 15, 16 |

Table 2 also displays the increasing channel distance d between the dual-channels for both spatial references. The reference stimulus was always a channel that was used in the dual-channel target (i.e., dual-channel 1, 2, 3, 4) was balanced against reference stimuli 1, 2 and 3, 4 separately).

The results from this and the following experiment define current compensation (CC) in dB as a function of dual-channel distance d in mm gained from the electrode spacing in the respective electrode arrays. CC is the amount of compensation for each individual channel in the dual-channel target necessary to result in a similar perceived loudness as the single-channel reference. The smallest possible distance of a dual-channel stimulus is two spaces because the center of each channel is situated in between the physical electrodes due to the fixed α of 0.5 (1, 2, 3, 4) results in the voltage peaks being situated at 1.5 and 3.5. Depending on the electrode spacing with either 0.85 mm for the Helix implant or 0.975 mm for the Mid-Scala/1j implant this is 1.70 mm or 1.95 mm, respectively. The equation to describe CC for the MCL loudness balancing condition in dB is

\[
CC = \frac{(l_{\text{ref1}} - 1) + (l_{\text{ref2}} - 1)}{2},
\]

with \(l_1\) and \(l_2\) as the current in dB of the first and second channel of the dual-channel target as well as \(l_{\text{ref1}}\) as the first component single-channel reference level for the first loudness balancing procedure and \(l_{\text{ref2}}\) as the second component single-channel reference level for the second balancing. See also Fig. 1 for reference.

2.4. Experiment 2: Threshold detection with single and dual-channel stimuli

To investigate whether the effect of channel distance on loudness summation is dependent on the presentation level, seven participants (CI01, 03, 07, 09, 10, 11 and 15) performed the first experiment at threshold level using a threshold (THL) detection paradigm. An adaptive 3 interval, 3 alternative forced-choice (3AFC) experiment was used for each stimulus that was tested in the MCL loudness balancing procedure (see Table 2).

In the main AFC task, the participants had to choose one of three visually sequentially highlighted intervals, one of which contained the test stimulus. The single channel stimuli started at a current of 50% (6 dB down) of the MCL value that the participants set in the loudness scaling procedure the current was reduced each time the test stimulus was detected twice in row, and increased after each incorrect response (2-down 1-up rule, Levitt, 1971). The starting step size was 2.51 dB and was reduced by half after each reversal to a minimum step size of 0.31 dB. The run terminated after eight reversals and the current levels at the last four reversals (when the minimum step size was reached) were averaged to obtain the threshold estimate.

For the dual-channel stimuli, the current ratio between the channels in the two component virtual channels was set equal to the current ratio of the two single-channel AFC thresholds. Using a 0.25 dB step size, the participant increased the loudness of the two-channel stimulus with the rotational controller until it was perceived as pleasantly loud. When each channel composition (see “Target Signal” in Table 2) was set to pleasantly loud three times, it served as the starting point for the second AFC threshold detection experiment with the dual-channel stimulus.

2.5. Experiment 3: Loudness balancing with unequal current between channels in the dual-channel stimuli

The effect on CC of having different current ratios between channels of dual-channel stimuli was investigated in nine participants (CI01 to 04, 09, 11, 12, 14 and 15). First, single-channels 5, 6, 8, 9, 10, 11, 12, 13 and 14, 15 were loudness scaled to MCL. Then, the dynamic ranges of the dual-channels [5, 6, 8, 9], [5, 6, 10, 11], [5, 6, 12, 13] and [5, 6, 14, 15] with the ratio of components set to those at MCL were determined. First, keeping the ratio constant, the currents in the dual-channel stimuli were loudness...
balanced to the single-channel stimulus 5.6 at MCL. Afterwards, the thresholds of the dual-channels were determined by adjusting the stimulation current until the stimuli were barely perceived. Finally, three different dual-channel stimuli were constructed using different current ratios (defined as the amount of reduction r). The second channel (either 8.9, 10.11, 12.13 or 14.15) of the dual-channel reference was reduced in current by \( r = 25\% / 0.25 \), \( r = 50\% / 0.50 \) and \( r = 75\% / 0.75 \) of its corresponding dual-channel dynamic range (also in current) while the other was kept at the original value. Each component channel was reduced in current in the same way. A single-channel stimulus, namely 5.6, was used as target and loudness balanced with the rotational controller to elicit the same loudness percept as the dual-channel stimuli with different current ratios. In this particular setup, the adjustment in dB current of the single-channel target stimulus with respect to its original MCL value (equal in loudness to the dual-channel with balanced currents) was used. Therefore, the current reduction of the target stimulus (resulting from the current difference in dB between the adjusted target in dB re. 1μA value and the original MCL value of it) reflects the CC which results from the application of the current ratios.

As a more practical example: a participant adjusted - individually - channel 5.6 to MCL at 150 μA and channel 8.9 at 120 μA. Next, stimulus [5.6, 8.9] is adjusted to MCL with the current amplitudes from the first step. The adjustment starts at zero and with the rotation of the controller, the current amplitude is increased (the step size is larger for the first dual-channel due to its higher current amplitude at MCL). In this example, our participant sets the current amplitudes for the individual channels of [5.6, 8.9] in dB lower (with respect to the original MCL values acquired at the first step) to 106 μA and 85 μA, respectively. Next, the same method is applied to gather the THL of the same stimulus. After the threshold detection, the participant set the current amplitudes to 37 μA for 5.6 and 30 μA for 8.9 in the [5.6, 8.9] stimulus, resulting from a reduction of 9 dB of the MCL values. The effective dynamic range of [5.6, 8.9] is acquired and represents the basis for the unequal current ratio stimuli. Channel 5.6 is fixed in its current amplitude, stimulating at MCL with 106 μA. The stimulating current amplitude of channel 8.9, however, is now reduced with \((MCL - THL) \cdot (1 - r) / THL \cdot 25\% (71 \mu A), 50\% (58 \mu A) or 75\% (44 \mu A)\) of its effective dynamic range for the individual, unequal current ratios. For the \( r = 75\% \) condition, stimulus [5.6, 8.9] is stimulating with 106 μA for channel 5.6 and 54 μA for channel 8.9. This stimulus is now being loudness balanced to the original single-channel stimulus 5.6 at 150 μA MCL.

2.6. McKay model for predicting loudness of electric stimuli

The McKay model to predict loudness for sequential electrical pulses by McKay et al. (2003) consists of various steps depicted in Fig. 1 into loudness contributions (2) is done by

\[
\log(L) = a \cdot CL + 0.03 \cdot b \cdot e^{-cL} + k
\]

with \( L \) the loudness contribution per pulse, a the slope of the linear part of the loudness growth function, CL the specific clinical amplitude of a stimulating pulse, \( b \) the slope of the exponential part, \( c_0 \) the knee point level of the transition between the linear and exponential part and \( k \) a constant to set the loudness contributions to a reference value. The relation between clinical amplitude units CL and current \( i \) in μA for the CI24M implant used in the McKay et al. (2003) study is given by

\[
i = 10 \cdot 175^{CL/255}
\]

The electrogram is now a representation of loudness contributions across channels over time. The second step is to choose a specific length for the temporal integration window. In both studies of Francart and McKay (Francart et al., 2014; McKay et al., 2003), a temporal integration window length of 2 ms was chosen. After summation across channels, the loudness contributions are temporally integrated in the 2 ms bins to result in loudness samples over time (step 3 in Fig. 2). This loudness is for stationary signals only, because the study from McKay et al. (2003) conducted experiments with periodic stimulation patterns only.

To extend the McKay model for time-varying stimuli, Francart et al. (2014) used the output of the McKay model as the input for the loudness model for time-varying stimuli (TVL) by Moore & Glasberg (2002). More specifically, they used the loudness estimate from step 3 as the instantaneous loudness of the TVL model (step 4). For the computation of the short-term loudness, the instantaneous loudness is temporally integrated with a recursive low pass filter of order 1 and an attack time constant of 45 ms and a release time constant of 20 ms (5). Next, to generate the long-term loudness the same procedure is performed on the short-term loudness with an attack time constant of 10 ms and a release time constant of 0.5 ms (6), which finally results in long-term loudness, the actual measure of loudness over time in sone (7). For further details see Moore & Glasberg (2002). In conjunction with this model, the electrogram can be used to estimate loudness contributions for time-varying stimuli. The extension by Francart et al. (2014) and the McKay model did not include the loudness prediction for simultaneously activated channels. It is therefore desirable to adapt the existing McKay model for the prediction of loudness for simultaneously activated channels. In this study we achieved this by using the above measurements to derive equally loud hypothetical single-channel pulses that can replace each simultaneous dual pulse in the model. To keep the adaptation of the model as practical as the original, generic values for the loudness growth function were chosen to evaluate the general applicability on a number of different CI users with various threshold and most comfortable levels as well as pulse rate and width. Note that in the model presented here, the current amplitudes of both electrodes in a channel are summed during the pre-processing of the stimulus, so that the model processes two current amplitudes per dual-channel.
2.7. Experiment 4: Validation of the adapted McKay model

To generate measured data for the validation of the adapted McKay model, Paired sound coding strategies based on the F120 strategy with different dual-channel distances (d = 2, 4, 6 and 8 electrodes channel distance, denoted by Paired2/4/6/8 in Fig. 3) were created and fit with the BEPS+ software (Advanced Bionics, Valencia, CA, USA) for participants CI01 to 03 and 06 to 11. The sequential F120 strategy (for a description see Nogueira et al., 2009) was fit as a baseline by setting single-channel pulse trains, channel by channel (the first channel corresponded to electrodes 1 and 2, the last channel to 15 and 16), to pleasant loudness (a category of 6 on the loudness scaling sheet). Thresholds were set at 10% of the fit MCL. Afterwards, the strategy was tested in free-field and the current values across all electrodes adjusted in 1 µA steps, so that the participant perceived the speech-shaped “Comité Consultatif International Télégraphique et Téléphonique” (CCITT) noise, presented at 65 dB SPL, at pleasant loudness as well. Finally, a loudness balancing with the same CCITT noise between all five strategies (Sequential and the four Paired versions) was performed to ensure that each strategy resulted in the same loudness percept. If a loudness difference occurred, the current values in clinical units were globally changed accordingly. Each balancing was performed three times for each pair of sound coding strategies until the participant stated no loudness differences between them. This resulted in five sound coding strategies with different fittings (MCL and the respective THL at 10% of the MCL) that resulted in the same loudness percept.

2.8. Statistical analysis

SPSS statistical software (IBM Corp. Released 2013. IBM SPSS Statistics for Windows) was used to perform a linear mixed model with list-wise deletion for the first two experiments due to missing data (experiment 1: the last two distances for the apical part across all subjects are missing, for the basal part two data points for ID01, three for ID02, six for ID03 and three for ID13 are missing; experiment 2: one data point for ID10 and two for ID15 missing) and a two-way repeated-measures analysis of variance (ANOVA) for the third experiment. For the linear mixed models, the effects of spatial reference and distance on CC were examined. For the ANOVA (only experiment 3), the effects of distance and ratio on CC were examined.

3. Results

3.1. Experiment 1: Loudness balancing between single and dual-channel stimuli at MCL

Fig. 4 presents the individual results of the loudness balancing procedure at MCL for the apical and basal references. The results are given as the channel compensation coefficient CC in dB across electrode distance d in mm. Linear fits are calculated for each subject and a general fit based on the average of the individual fits is generated as well (displayed as the red, dashed line). The analysis was performed separately for apical and basal regions. To do this, all data points for the dual-channel stimuli that are in the basal/apical regions (i.e., all data with component channels that are both between 8.9 and 15.16, compared to all data with component channels both between 1.2 and 8.9) were selected and compared to each other. There was a statistically significant effect of spatial reference (F(1, 304) = 57.321, p < .001) and distance (F(12, 304) = 14.925, p < .001) on CC, but no interaction between distance and spatial reference (F(1304) = 3.849, p = .156). In general, high CC was observed at small distances between the dual-channels and low CC was observed at large distances, observing a negative slope. The spread of CC across individuals was significantly smaller for the basal region than for the apical one (F(1,10) = 5.33, p = .043). The latter was also observed in subjects whose CC did not change over distance (ID07 and 11).

3.2. Experiment 2: Threshold detection with single and dual-channel stimuli

Fig. 5 presents the CC in dB between detection thresholds of single and dual-channel stimuli as a function of d in mm. Similar to the measurement in experiment 1, CC increases with decreasing distance between dual-stimuli. The basal reference also shows less spread of CC across participants at each individual distance with ID07 and ID09 showing almost no change of CC across distance. Again, a linear mixed model was performed to examine an effect of spatial reference and distance on CC. There was no significant effect of spatial reference (F(1, 241) = 0.032, p = .857) but a significant effect of distance (F(12, 241) = 8.689, p < .001). There was also no significant interaction between both factors (F(1241) = 8.807, p = .390).

3.3. Experiment 3: Loudness balancing with unequal loudness between channels in the dual-channel stimuli

Fig. 6 shows the current difference in dB between the original loudness scaled MCL value of the single channel 5.6 and the adjusted value of the same stimulus when loudness balanced against a dual-channel reference with different current ratios. If no reduction on a component single channel is applied, a current difference of 0 dB is achieved, because reference and target were loudness balanced to MCL. There was a statistically significant effect of ratio (F(2, 16206) = 7.558, p = .013, with Greenhouse-Geisser correction), but not of distance (F(3, 45) = 3.456, p = .058) on current difference. The interaction between distance and ratio on current difference was also not significant (F(6, 156) = 0.922, p = .481). For the ratios, significant differences between r = 25% and 75% current
reduction for all electrode distances were found \((p < .01)\). A one-sample \(t\)-test with Bonferroni correction applied was performed to check if the various conditions were significantly different from the reference stimulus (zero line). All conditions were significantly different with \(p < .01\). The mean current difference across conditions was 1.63 dB.

### 3.4. McKay model adaptation

The results from the previous experiments were used to adapt the McKay model for the prediction of loudness of complex electrical stimuli from McKay et al. (2003) and its extension by Francart et al. (2014) for simultaneous stimulation.

The principle of the adaptation is relatively simple. Each simultaneous pair of pulses in a dual-channel activation is theoretically converted to a single pulse on one channel that has the same loudness as the original dual-channel pulse. This then allows the loudness model for sequential stimulation pulses to be applied as usual. To do this conversion, the current of the component channel with the highest current in a simultaneous dual-channel pair is increased with the CC corresponding to the distance \(d\) between the dual channels (see CC in Eq. (4) and Fig. 7). Depending on the current ratio \(r\) between the channels, compensation is high for an equally-loud dual-channel pairs or less when one of the channels is almost stimulated alone. In the extended model, the component

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**Fig. 4.** Current compensation (CC) as a function of distance in mm between the dual-channel at most comfortable level for basal only data points (left) and apical only data points (right). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Fig. 5.** Current compensation (CC) as a function of distance in mm between the dual-channel at threshold for basal only data points (left), apical only data points (right). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
channel of the pair with the lowest current is ignored and the one with the highest current is modified with the following current in dB: i.e.

$$SC = I_{\text{max}} + CC_{1}(d) + CC_{2}(r, d),$$  \hspace{1cm} (4)

with SC as the final stimulation current after compensation and $I_{\text{max}}$ the current of the highest channel of the dual-channel in an electrodogram in dB re 1 $\mu$A. To calculate the CC required for the conversion in the model, the effect of spatial reference was ignored. To incorporate dual-electrode stimulation (virtual channel/adjacent electrodes only), it is assumed that the smallest distance in the electrode array (see Section 2.3) necessitates a CC of 6 dB, as was calculated by Donaldson et al. (2005), Tang et al. (2011) as well as Busby et al. (2005). Therefore, the $CC_{1}$ function is derived from the results with distance $d$ in number of electrode spaces (integer ranging from 1 to maximum number of electrodes) according to

$$CC_{1}(d) = \left\{ \begin{array}{ll} \frac{6}{4.525 - 0.2153 \cdot d}, & \text{if } d \geq 1 \\ \frac{6}{4.525 - 0.2153 \cdot d}, & \text{if } d \geq 2 \end{array} \right.$$  \hspace{1cm} (5)

and current ratio $r$ (derived from % DR) in the area between 0.25 and 0.75 according to the linear function (which resulted in the highest $r = 0.970$ from a linear regression calculation with $F(1,3) = 22.2, p = .018$) derived from a pooling of data from experiment 3 as follows:

$$CC_{2}(r, d) = \left\{ \begin{array}{ll} 5.368 r - 1.127 r - 1.061 \cdot \frac{(r - 0.75) - 1.906}{0.25} \cdot 0.75 & \text{if } 0 < r < 0.25 \\ 5.368 r - 1.127 r - 1.061 \cdot \frac{(r - 0.75) - 1.906}{0.25} \cdot 0.75 & \text{if } 0.25 \leq r \leq 0.75 \end{array} \right.$$  \hspace{1cm} (6)

An $r = 0$ (no reduction) does not necessitate any CC other than the one derived from distance, while an $r = 1$ (full reduction, ergo single-channel stimulation) does not necessitate the application of CC whatsoever. The non-measured regions ($0 \leq r < 0.25$ and 0.75 $< r \leq 1$) are interpolated linearly to cover these ratios.

We kept the parameter $a$ of the McKay model (see Eq. (2)) according to McKay et al. (2001) at 0.019. To perform a comparison between two stimuli using the McKay model, a reference stimulus is set to a certain Sone value (e.g. 16 Sone is considered to correspond with comfortable loudness) by adjusting the constant $k$ in Eq. (2). This $k$ value is then applied to the target as well and the difference in sone can be calculated. The rest of the method remains unchanged as explained in Section 2.6.

3.5. Experiment 4: Validation of the adapted McKay model

Fig. 8 shows the measured current difference in dB for the four Paired sound coding strategies (shown as electrode distances for each subplot) of the participants (F10Diff) and three
McKay model adaptation variants (D, DR and No CC) that are described in the following text. To investigate what effect each investigated measure (distance and current ratio) has on the output of the model, three variants of the extension of the McKay model were evaluated. Note that the loudness predictions for Sequential as the reference are performed with the original McKay model. By introducing more variables into the CC function, the performance/prediction of the McKay model was expected to improve (effectively being more similar to FitDKE). Variant D used the averaged function from experiments 1 and 2 (as shown in Figs. 4, 5 and Eq. (5)) as CC only, without taking the current ratio between dual-channels into account. Variant DR includes – besides the averaged function from variant D – the effect of current ratio between dual-channels found in experiment 3, which follows the idea that the current compensation for equally loud dual-channels is too strong if the current ratio is unequal between the dual-channels (therefore necessitating a softer compensation). Eq. (6) is used for the reduction of CC depending only on the current ratio. Effectively, if the current ratio is high (the component single channel with less current is very small compared to the channel with the highest current), then the reduction of CC is low and vice versa. The “No CC” variant finally investigates the case where no compensation is applied and only the highest current in a dual-channel is chosen for the loudness prediction. This case is equivalent to a Paired strategy, but where only one channel of each pair of channels is activated. It is expected that the model predicts Sequential to have higher currents than the compensated Paired strategies.

With regards to the behaviorally measured FitDiff results, the Sequential strategy resulted in the highest current amplitudes compared to the Paired strategies (a one-sample t-test resulted in mean current difference CD between Sequential and Paired2 = 3.14 dB, p < .001; Paired4 = −2.59, p < .001; Paired6 = −1.63 dB, p < .001; and Paired8 = −0.89 dB, p = .002). The amplitude currents decreased with decreasing distance between simultaneous stimulating channels, showing Paired2 as the strategy with the lowest amplitudes across strategies with a CD value of −3.1 dB on average and Paired8 as the strategy with current amplitudes closest to the values of Sequential with a CD value of −0.85 dB. Therefore, electrodograms with CCIT noise as input were generated with Sequential and the aforementioned Paired strategies, fit to the amplitude values of Sequential. We hypothesized that the loudness model, using the CC as in Eq. (4), will predict the current difference of these electrodograms according to the behavioral data FitDiff in Fig. 8.

To evaluate this hypothesis, each individual current pulse of the input electrodogram of Paired4/6/8 was modified in dB with the variable CD when a difference in predicted Sone to Sequential was present (similar to a complete shift of MCL and THL in the fit of the patient). This current modification with CD of the electrodogram was performed until the McKay model predicted the same loudness in Sone as Sequential. In the best case, the predicted CD should be similar to the FitDiff value when our adaptation of the model is applied.

A two-way ANOVA with correction for multiple comparisons (number of method variants) was performed to check the hypothesis that the loudness predictions with our adaptation of McKay’s model varied in a similar way to the measured data. Overall, there was an effect of the variants of the adaptation (F(3, 128) = 221.223, p < .001) and of distance (F(3, 128) = 57.208, p < .001) on the difference between Sequential and Paired loudness predictions. Tukey post hoc tests for the variants of the extension revealed significant differences between the measured data FitDiff and the variant D (mean difference = −1.04 dB, p < .001) and No CC (mean difference = 1.96 dB, p < .001). There was no statistically significant difference between FitDiff and variant DR predictions (mean difference = −0.24 dB, p = 1.000). Tukey post hoc tests for the distances revealed overall statistically significant differences between all distances (p < .001). This means that the model DR including the effect of CC on distance d and current ratio r is the most accurate.

4. Discussion

This study investigated the effect of distance and current ratio between pairs of virtual channels on the loudness of dual-channel stimulation. The insights gained, helped to understand loudness perception for simultaneous virtual channel stimulation and showed the feasibility of a state-of-the-art model to predict loudness from this form of electric stimulation. A clear dependence of loudness on distance between channels was observed with current compensation changing at a slope of 0.24 dB/j mm on average. A lack of statistical significance of the effect of presentation level on current compensation suggests that the absolute current level may not affect electrical interaction due to simultaneous channel stimulation (at least on the dB scale). Unequal current ratios lead to a decrease in current compensation. The insights led to an application of the McKay model for loudness modeling with CI stimulation (McKay et al., 2003), which produced a small prediction error of loudness for sound coding strategies based on simultaneous stimulation.

Two channels stimulated simultaneously in phase generally elicit a higher loudness perception when compared to the same electrodes being activated sequentially (Frijns et al., 2009; Marozeau et al., 2015; Snel-Bongers et al., 2013). The magnitude of this electrical interaction depends on the electrode distance between the dual-channel stimuli as illustrated in the first two experiments. The fact that a CC of 0 dB is only observed once by any of the participants (see Fig. 5) shows that loudness summation can be present even for the largest electrode distance with dual-channel stimulation. It can be expected that loudness summation still occurs even if the pulses are stimulated sequentially, although this interaction is not due to current summation. Marozeau et al. (2015) found similar effects of distance with simultaneous monopolar stimuli with a sequential monopolar stimulus as a reference. The results showed current compensation (labeled level difference in the paper) at a distance of 1 electrode to be around 4 dB, continually decreasing with increasing distance of up to 4.8 mm. The findings of Landsberger and Galvin (2011) state...
that sequential virtual channels required 5 dB more current than a simultaneous one at a channel distance of one electrode, which resembles our findings with virtual dual-channel stimulation of roughly 4.5 dB at the same channel distance, although we did not compare sequential dual-channels but single-channels to simultaneous dual-channels.

While most participants showed a similar behavior and slope with CC across distance, three of the ten participants (ID01, 02 and 11) showed descriptively different results for the apical and basal reference conditions. All of the mentioned participants’ data in the basal reference condition resulted in slopes that followed the general fit (see dashed red line in left-hand plot of Fig. 4), while their basal counterpart resulted in very shallow slopes (right-hand plot of Fig. 4). These results contradict our assumption that electrical interactions behave similarly across the electrode array. However, there are three possible alternative explanations for this behavior: first, the initial loudness balancing procedure of the single-channel stimuli in the first two experiments was performed sequentially across the array. Any systematic bias or experimental error that would occur in the beginning of the balancing would continue on to the end of the procedure and would make the differences larger and the balancing less accurate. This might also be the reason why the spread in CC for larger d’s in the basal and overall in the apical spatial reference is greater compared to the smaller distances in the basal spatial reference, flattening the regression slope. Second, the loudness balancing procedure with a high frequency / basal stimulation might have been too difficult for these participants and therefore introduced errors already mentioned in the former paragraph. The discomfort often associated with high frequency stimulation was also stated by a number of participants in this study. An old study from Steinberg & Munson (1936) also showed larger standard deviations for loudness balancing a 5 kHz pure tone target with a 1 kHz reference than with a 100 Hz target in normal hearing (this was, however, not replicated with CI users). Finally, some data points were missing, especially for the smallest distance, for participant ID02 and ID11. We suspect that the smallest possible distance would have resulted in a higher CC for both participants and would have affected the linear fit to result in a steeper slope.

Another important aspect of this study is our assumption that virtual channels create electrical fields similar to single electrodes. Unfortunately, no study has investigated if simultaneous stimulation with two virtual channels (both with α set to 0.5) creates an electric field that is similar to the electric field created by single...
electrodes stimulating simultaneously. Sound coding strategies that use simultaneous virtual channels assume similarity with physical electrode stimulation. SoBonham & Litvak (2008)reviewed several studies that highlighted the similarity of physical electrode vs. current steered channel stimulation. Two studies from Bonham et al. (2007, 2006) performed measurements in the inferior colliculus (IC) of anesthetized guinea pigs to characterize the spatial response profiles of current steered channels. A current steered channel did – above a certain stimulus level near threshold - elicit a similar response as a physical electrode in terms of response strength and width across the IC depth. Another indication of similarity in humans comes from Snel-Bongers et al. (2012), who investigated channel interaction with a threshold detection experiment and spread of excitation based on eCAP measurements between single-electrode and dual-electrode stimulation. They concluded that the two modalities showed no difference in terms of spread of excitation and channel interaction. These studies were able to demonstrate that current steered stimulation produces similar responses to physical electrodes.

The lack of a significant effect of presentation level (THL or MCL) on CC in our study was also reported in the study of Landsberger and Galvin (2011) as well. Both findings contradict the findings of Snel-Bongers et al. (2011) who found a significant effect of presentation level. It is important to note that Snel-Bongers et al. investigated the possibility to create spanning and with it an intermediate place pitch, while our study and the sound processing strategies assume that dual-channel stimulation conveys different information in each channel. However, the results of our study are consistent with the findings of their study on the effect of current compensation with increasing distance between electrode contacts: if the distance between simultaneous stimulating electrodes is increased, less current reduction is necessary to reach the same loudness as single electrode stimulation. Snel-Bongers additionally reported a current compensation of 0.52 dB (mm on average (Snel-Bongers et al., 2011). Our overall averaged slope (0.24 dB/mm) is roughly half of this value, which can be partially explained by four differences: I) electrode arrays used (Snel-Bongers et al. used lateral wall 1) arrays, while this study had participants with modiolus-hugging Helix and the in-between solution Mid-Scala); II) electrode spacing; III) usage of dual-electrode vs. our dual-channels and IV) overall subject variability.

The measurement with unequal current ratios between channels (experiment 3) showed that with a higher reduction of an individual channel in the dual-channel reference (going from 25% to 75%), the current difference of the target between adjusted and MCL value increased (lower value in Fig. 6). An effect of distance was not found, because the references (dual-channels with both channels at 100% dynamic range) were set to equal loudness at MCL and thus are already adjusted for effect of distance. However, the effect of ratio is statistically significant and demonstrates that the reduction of one channel in the dual-channel stimulus from 75% to 25% results in a statistically significant difference in loudness.

The results of the final version of the McKay model (DR) seem the most promising with an average non-significant difference to the measured FLdiff results of 0.24 dB (D resulted in a 1.04 dB averaged current difference). The extension DR was based on the fact that the ratio had a significant effect on the current difference shown in the third experiment, leading to a statistically significant reduction of the prediction error with respect to variant D and showing a lack of statistical difference to the measured FLdiff data (which variant D could not show). The adapted McKay model offers a practical method of predicting loudness for simultaneous sound coding strategies and to potentially change from sequential to simultaneous stimulation in a sound coding strategy based on the loudness predictions. Due to the small number of participants more data is necessary to state that the adaptation is applicable on the general population of CI users.

Conclusions

The results of several psychoacoustic experiments highlighted the difference in loudness between single channel and dual-channel stimulation and provided the data to adapt the McKay loudness model for simultaneous stimulation. A simple electrogram conversion that used the strongest stimulating channel with a certain compensation value kept this adaptation practical and makes it possible to evaluate the effect of new simultaneously stimulating sound coding strategies on the percept of loudness. The adaptation now needs to be tested and optimized in a larger group of subjects.

CRediT authorship contribution statement

Floriano Langner: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization. Colette M. McKay: Conceptualization, Methodology, Validation, Resources, Writing - review & editing. Andreas Büchner: Methodology, Resources, Writing - review & editing, Funding acquisition. Waldon Nogueira: Conceptualization, Methodology, Validation, Resources, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition.

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