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1 **Effect of Channel Interaction on Vocal Cue Perception in**

2 **Cochlear Implant Users**

3

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17 **ABSTRACT**

18 Speech intelligibility in multi-talker settings is challenging for most CI users. One possibility
19 for this limitation is the suboptimal representation of vocal cues in implant processing, such as
20 the fundamental frequency (F0), and the vocal tract length (VTL). Previous studies suggested
21 that while F0 perception depends on both spectral and temporal cues, VTL perception relies
22 largely on spectral cues. To investigate how spectral smearing in CIs affects vocal cue
23 perception in speech-on-speech (SoS) settings, parallel channels were simultaneously
24 stimulated in 14 Advanced Bionics users to simulate channel interaction. Three such patterns
25 were created: Sequential (stimulation of 2 simultaneous electrodes), Paired (4 electrodes), and
26 Triplet stimulation (6 electrodes). F0 and VTL just-noticeable differences (JNDs; task 1), in
27 addition to SoS intelligibility (task 2) and comprehension (task 3) were measured for each
28 stimulation strategy. In tasks 2 and 3, four maskers were used: the same female talker, a male
29 voice obtained by manipulating both F0 and VTL (F0+VTL) of the original female speaker, a
30 voice where only F0 was manipulated, and a voice where only VTL was manipulated. JNDs
31 were measured relative to the original voice for the F0, VTL, and F0+VTL manipulations.
32 When spectral smearing was increased, a significant deterioration in performance was observed
33 for all tasks, with no differences between Sequential and Paired stimulation. These results imply
34 that CI users may tolerate certain amounts of channel interaction without significant reduction
35 in performance on tasks relying on voice perception. This points to possibilities for utilizing
36 parallel stimulation in CIs for reducing power consumption.

37 Keywords: channel interaction; cochlear implant; speech-on-speech; F0; VTL

38 **INTRODUCTION**

39 Cochlear implants (CIs) are devices that can restore hearing in people suffering from profound
40 hearing loss. Although many CI users obtain good speech performance in quiet, their speech
41 intelligibility drops significantly in the presence of two or more simultaneous speakers (e.g.,

42 Cullington & Zeng, 2008). The performance of CI users in such a speech-on-speech (SoS)
43 scenario has been shown in a previous study (El Boghdady, Gaudrain, & Başkent, 2019) to be
44 correlated with their sensitivity to two important voice cues defining the voices of the target
45 and masker speakers: the fundamental frequency (F0) and the vocal tract length (VTL) of the
46 speaker.

47 The speaker's F0 induces the percept of the voice pitch and is usually lower for adult males
48 than adult females (Peterson & Barney, 1952; Smith & Patterson, 2005). These F0 cues are
49 usually encoded in both the temporal envelope and the cochlear location of excitation (e.g.,
50 Carlyon & Shackleton, 1994; Licklider, 1954; Oxenham, 2008), which gives these cues a
51 spectrotemporal nature.

52 The VTL correlates with the speaker's physical (Fitch & Giedd, 1999) and perceived height
53 (Ives, Smith, & Patterson, 2005; Smith, Patterson, Turner, Kawahara, & Irino, 2005), and is
54 usually longer for adult males than for adult females. VTL cues are usually represented through
55 the speech spectral envelope (Chiba & Kajiyama, 1941; Fant, 1960; Lieberman & Blumstein,
56 1988; Müller, 1848; Stevens & House, 1955). Shortening VTL results in the stretching of the
57 spectral envelope towards higher frequencies on a linear frequency scale, while elongating VTL
58 results in the compression of the spectral envelope towards lower frequencies. This means that
59 VTL cues can be largely encoded in the relationship between the peaks in the spectral envelope
60 of the signal. Hence, the adequate representation of both F0 and VTL cues would be expected
61 to require sufficient spectrotemporal resolution.

62 Information transmitted by the CI is usually spectrotemporally degraded (Fu & Nogaki, 2005;
63 Fu, Shannon, & Wang, 1998; Henry & Turner, 2003; Nelson & Jin, 2004; Winn, Won, & Moon,
64 2016). Spectrotemporal resolution in the implant depends on a number of factors, such as the
65 amount of channel interaction between adjacent electrodes and the subsequent effective number
66 of spectral channels (for a review, see Başkent, Gaudrain, Tamati, & Wagner, 2016). Because

67 of the conductive fluid filling the cochlea, current spreads between neighboring electrodes
68 resulting in channel interaction (e.g. Boëx, de Balthasar, Kós, & Pelizzone, 2003; De Balthasar
69 et al., 2003; Hanekom & Shannon, 1998; Shannon, 1983; Townshend & White, 1987), and the
70 subsequent reduction in the effective number of spectral channels. The literature has
71 demonstrated that CI listeners do not usually have access to more than 8 effective spectral
72 channels (Friesen, Shannon, Başkent, & Wang, 2001; Qin & Oxenham, 2003) and that
73 significant channel interaction not only impairs speech and phoneme perception (e.g. Friesen
74 et al., 2001; Fu & Shannon, 2002; Qin & Oxenham, 2003), but also voice cues as well (Gaudrain
75 & Başkent, 2015). In the latter study, Gaudrain and Başkent (2015), using vocoder simulations
76 of CI processing, have demonstrated that as channel interaction increases (simulated as the
77 shallowness of the vocoder filter slopes), the sensitivity to VTL cues deteriorates. Thus, the
78 poor spectrotemporal resolution in CIs is also expected to influence voice differences between
79 target and masker speakers in SoS scenarios.

80 This study aims at assessing the effects of such channel interaction (and resulting spectral
81 resolution) on SoS and voice cue perception in CI listeners by using simultaneous stimulation
82 of different channels. Beyond the purpose of understanding how crucial spectrotemporal cues
83 are for F0, VTL, and SoS perception, there is also a potential benefit in using parallel
84 stimulation, since it was originally proposed in the literature as a method of reducing power
85 consumption (e.g., Büchner, Frohne, Battmer, & Lenarz, 2005; Frijns, Kalkman, Vanpoucke,
86 Bongers, & Briaire, 2009; Langner, Saoji, Büchner, & Nogueira, 2017). One way of achieving
87 this is to decrease the maximum stimulation current required to stimulate the auditory nerve.
88 For instance, by stimulating two adjacent electrodes in the cochlea it is possible to reduce the
89 amount of current by half to achieve the same loudness percept as that from single electrode
90 stimulation, since the current is distributed between both electrodes. Additionally, it is possible
91 to introduce simultaneously stimulated parallel channels, for example Paired (two pairs of
92 simultaneous channels, with one channel consisting of 2 adjacent electrodes simultaneously

93 stimulated at a time) and Triplet stimulation (three pairs of simultaneous channels), to reduce
94 the maximum current delivered by the implant by a factor of 17% and 44%, respectively. With
95 Paired stimulation, it is possible to double the pulse duration with respect to Sequential
96 stimulation without changing the stimulation rate of the implant. In terms of performance,
97 Langner et al. (2017) showed no degradation of speech performance under stationary
98 background noise for Paired stimulation. However, the same study also showed that increasing
99 the number of parallel channels to three, such as in Triplet stimulation, causes a significant drop
100 in speech intelligibility in comparison to Sequential stimulation (a single pair of simultaneous
101 channels). From these results, it was suggested that Paired stimulation may be a good candidate
102 for reducing power consumption in CI users, however, more detailed speech performance
103 measures are required to assess the potential effects of adding parallel channels (spectral
104 smearing and channel interaction) on speech intelligibility. Thus, another goal of this study, if
105 only degradations were to be observed, was to determine the level of parallel channel
106 stimulation that could be acceptable for voice cue and SoS perception, without significant
107 reduction in performance.

108 Three research questions were addressed in this study: 1) whether increasing the number of
109 parallel stimulated channels (increasing channel interaction) decreases the sensitivity to F0 and
110 VTL differences in CI users (task 1), and 2) whether this effect is also reflected as a reduction
111 in SoS perception (tasks 2 and 3). The expectations were that these effects should be larger for
112 VTL compared to F0 perception, because VTL is a primarily spectral cue, while F0 cues could
113 still be preserved in the temporal aspect of the signal even if the spectral component is
114 compromised. The third research question was 3) whether some parallel channel stimulation
115 could be deployed for reducing power consumption without significantly impairing voice cue
116 and SoS perception.

117 I. METHODS

118 A. Participants

119 Twelve native German CI users with Advanced Bionics (AB) devices were recruited from the
120 clinical database of the Medizinische Hochschule Hannover (MHH) based on their clinical
121 speech intelligibility scores in quiet and in noise. To ensure that participants could perform the
122 SoS tasks, the inclusion criteria were to have a speech intelligibility score higher than 80% in
123 quiet and 20% in noise at a +10 dB signal-to-noise ratio on the Hochmair-Schulz-Moser (HSM)
124 sentence test (Hochmair-Desoyer, Schulz, Moser, & Schmidt, 1997). Table 1 shows the
125 demographics of the CI users. Only 8 (P05-P12) of the 12 participants participated in the SoS
126 comprehension task.

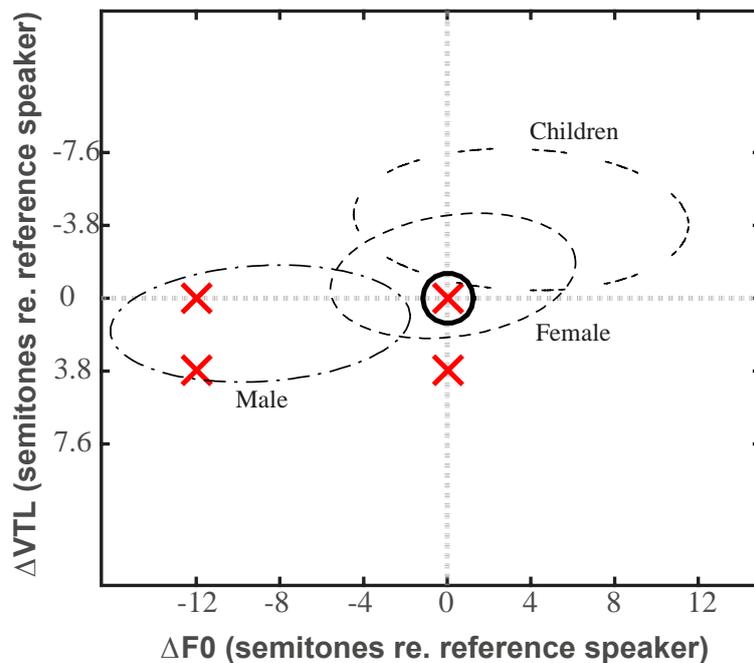
127 **Table 1.** Demographics for CI users recruited. All durations in years are calculated based on the date of
128 testing. Progressive hearing loss refers to participants who experienced minimal hearing loss that gradually
129 progressed until they fulfilled the criteria for acquiring a CI.

Participant number	Gender	Age at testing (y)	Implant	Duration of device use (y)	Duration of hearing loss (y)	Etiology	Clinical speech-in-quiet scores
P01	M	20	Helix	4.0	0	Unknown	100%
P02	F	48	Helix	8.7	0.61	Acute	100%
P03	M	55	Mid-Scala	3.8	Progressive	Unknown	96%
P04	M	58	Mid-Scala	2.5	Progressive	Unknown	100%
P05	M	47	Mid-Scala	5.5	1.5	Acute	100%
P06	M	43	Helix	10.5	Progressive	Acute	98.11%
P07	F	51	Helix	11.4	0	Genetic	90.56%
P08	F	70	Helix	2.6	5.24	Unknown	100%
P09	M	51	Mid-Scala	5.6	Progressive	Unknown	95.25%
P10	F	46	Helix	9.6	Progressive	Acute	100%
P11	F	49	Helix	8.2	0.05	Acute	70.75%
P12	M	65	Helix	10	Progressive	Unknown	99.06%

130

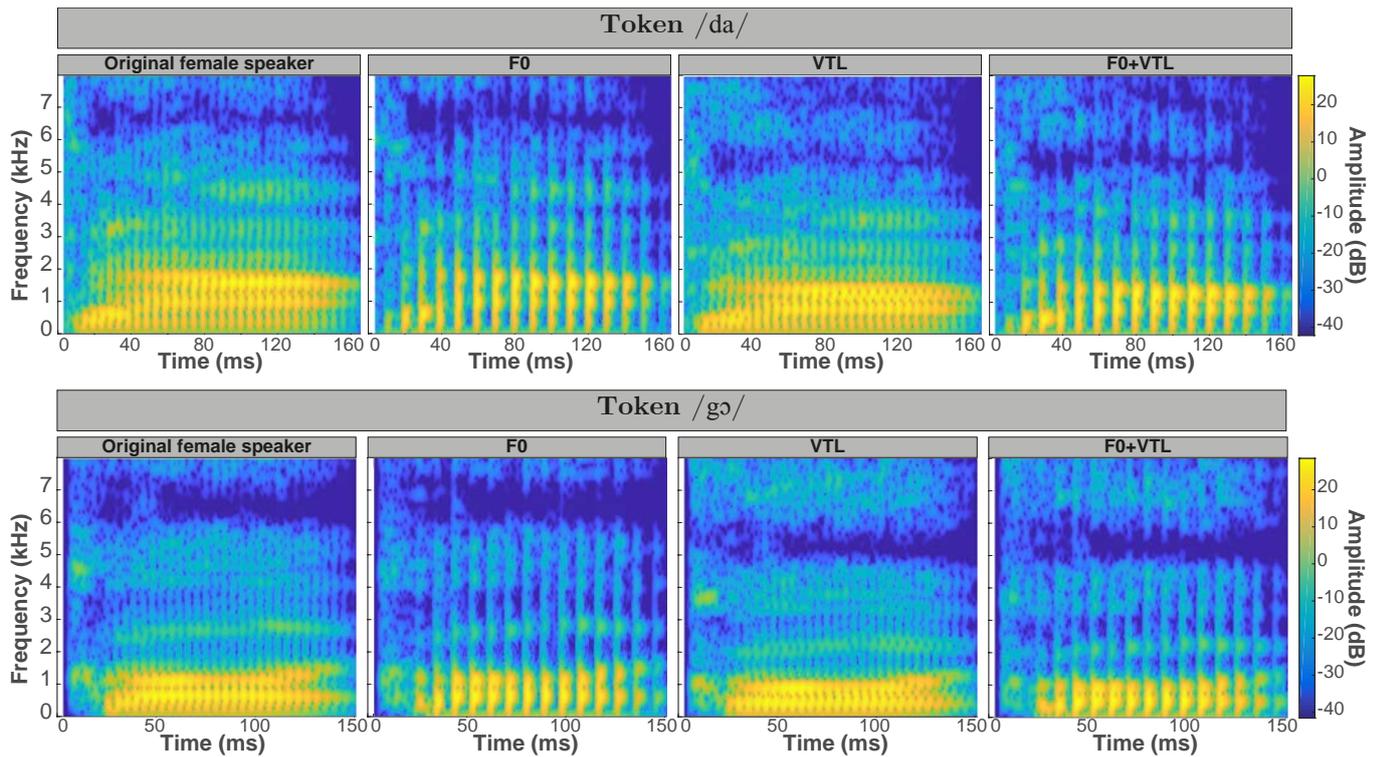
131 **B. Voice cue manipulations**

132 F0 and VTL cues were manipulated relative to those of the original speaker of the corpus in
 133 each experiment using the *Speech Transformation and Representation based on Adaptive*
 134 *Interpolation of weiGHTed spectrogram* (STRAIGHT; Kawahara & Irino, 2005).
 135 Increasing/decreasing F0 in STRAIGHT is implemented by shifting the pitch contour of the
 136 original speech upwards/downwards by a number of semitones (12th of an octave; st) towards
 137 higher/lower frequencies relative to the average F0 of the stimulus. Shortening/elongating VTL
 138 is implemented by expanding/compressing the spectral envelope of the signal towards
 139 higher/lower frequencies.



140
 141 Figure 1. $[\Delta F0, \Delta VTL]$ plane, with the reference female speaker from experiment 2 shown as the solid
 142 black circle at the origin of the plane. Decreasing F0 and elongating VTL yields deeper-sounding male-like voices,
 143 while increasing F0 and shortening VTL yields child-like voices. The dashed ellipses are based on the data from
 144 Peterson and Barney (1952), which were normalized to the reference female speaker, and indicate the ranges of
 145 typical F0 and VTL differences between the reference female speaker and 99% of the population. The red crosses
 146 indicate the voice vectors from the origin of the plane along which the JNDs were measured in experiment 1, and
 147 the 4 different combinations of $\Delta F0$ and ΔVTL used in both experiments 2 and 3.

148 Figure 1 shows the F0 and VTL values (red crosses) used in the current studies on the [ΔF_0 ,
149 ΔVTL] plane. The red crosses indicate the voice vectors (directions) from the origin of the plane
150 along which the JNDs were measured in experiment 3 (along negative ΔF_0 , along positive
151 ΔVTL , and along the diagonal passing through $\Delta F_0 = -12$ st, and $\Delta VTL = +3.8$ st). In addition,
152 they represent the 4 combinations of F0 and VTL differences between the masker and target
153 speakers in experiments 2 and 3. The solid black circle at the origin on the plane indicates the
154 voice of the original female speaker from the corpus used in experiment 2. The dashed ellipses
155 encompass the range of relative F0 and VTL differences between the original female speaker
156 99% of the population as calculated from the Peterson and Barney study (1952). This
157 calculation was performed by normalizing the data provided by Peterson and Barney relative
158 to the voice parameters of the original female speaker of the corpus, who had an average F0 of
159 about 218 Hz and an estimated VTL of around 13.97 cm. The original female speaker's VTL
160 was estimated using the method of Ives et al. (2005) and the data from Fitch and Giedd (1999),
161 assuming an average height of about 166 cm for the speaker based on growth curves for the
162 German population (Bonthuis et al., 2012; Schaffrath Rosario, Schienkiewitz, & Neuhauser,
163 2011). ΔVTL is oriented upside down to indicate that positive ΔVTL s yield a decrease in the
164 frequency components of the spectral envelope of the signal.



165

166 Figure 2. Spectrograms of two German tokens [/da/ (*top row*) and /go/ (*bottom row*)] shown for each voice.
 167 *First column from left:* original female speaker from the corpus; *second column from left:* effect of decreasing F0
 168 by 12 st on the spectrogram; *third column from left:* effect of elongating VTL by 3.8 st; *fourth column from left:*
 169 effect of both decreasing F0 by 12 st and elongating VTL by 3.8 st relative to the voice of the original female
 170 speaker.

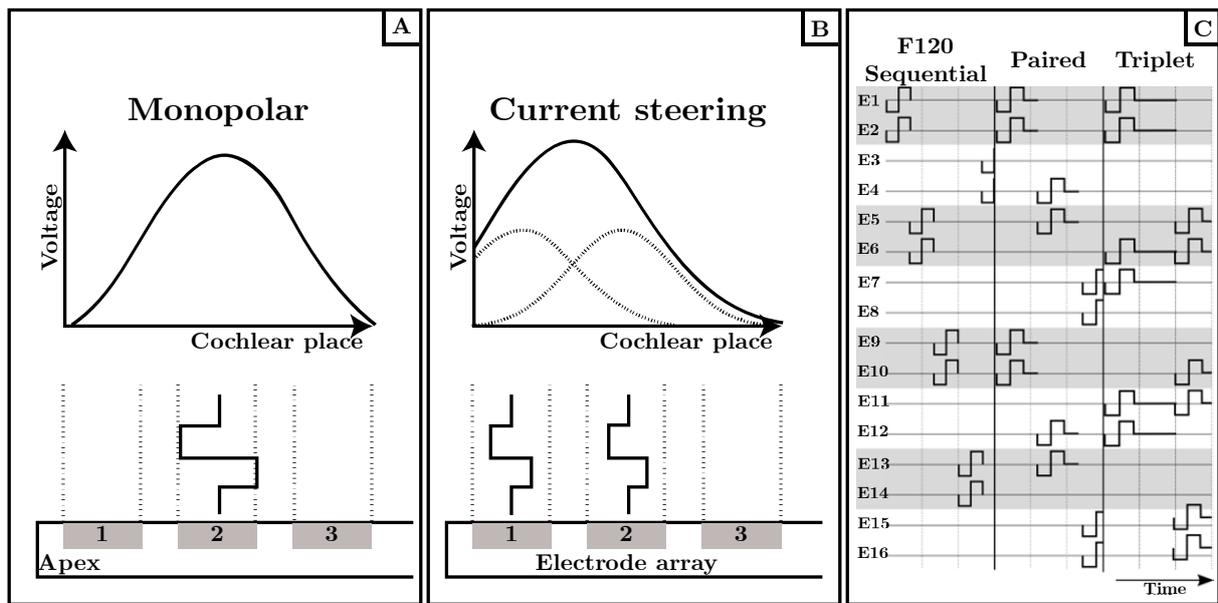
171 Figure 2 shows the effect of manipulating F0 and VTL on the spectrograms of two German
 172 tokens. The rows represent the different tokens, while the column represent the voice
 173 manipulation [no manipulation (original female speaker), F0, VTL, or both F0 and VTL].
 174 Notice that as F0 decreases, the number of glottal pulses also decreases, and as VTL is
 175 elongated, the spectral content of the signal is compressed towards lower frequencies along a
 176 linear frequency scale. In addition, decreasing F0 and elongating VTL together yield less glottal
 177 pulses which are also compressed towards lower frequencies.

178 **C. F120 Sound Coding Strategies (Sequential, Paired and**
179 **Triplet)**

180 **1. Fidelity F120 Sound Coding Strategy**

181 The Fidelity 120 (F120) in Advanced Bionics devices is a sound coding strategy that processes
182 the audio signal through an automatic gain control. Next, a spectral analysis is performed using
183 a short time fast Fourier transform (STFFT) to compute the slow varying envelopes in each
184 analysis band. In parallel, the spectrum is analyzed in more detail using a spectral peak locator
185 to estimate the most dominant frequency component in each analysis band. Finally, the slowly
186 varying envelopes are logarithmically compressed into the electric dynamic range of each
187 participant between the threshold and the most comfortable level. Each analysis band is
188 assigned to two simultaneously stimulated electrodes [Figure 3 (B)]. The current ratio between
189 these two electrodes is derived from the spectral peak locator forming a current steered – or
190 virtual – channel. For a given analysis band k , a pair of electrodes are simultaneously
191 stimulated, one with current $I_k \cdot \alpha$ and the adjacent one with current $I_k \cdot (1 - \alpha)$, with I_k being
192 the compressed current obtained from the envelope in analysis band k , and α being the current
193 steering coefficient ($0 \leq \alpha \leq 1$) derived from the spectral peak locator. Each analysis band k
194 ($k = 1 \dots N$) is stimulated sequentially [see Sequential stimulation panel in Figure 3 (C)],
195 completing a stimulation cycle. The Advanced Bionics CI has 16 electrodes and the F120 uses
196 $N = 15$ analysis bands.

197 Figure 3 (A) provides the concept of monopolar stimulation with its associated voltage spread.
198 Figure 3 (B) demonstrates the concept of current steering (virtual channel) stimulation. With
199 Paired and Triplet stimulation [Figure 3 (C)], each pulse is extended with zero stimulation after
200 the end of the second biphasic pulse to keep the stimulation rate on each channel constant across
201 sound coding strategies.



202

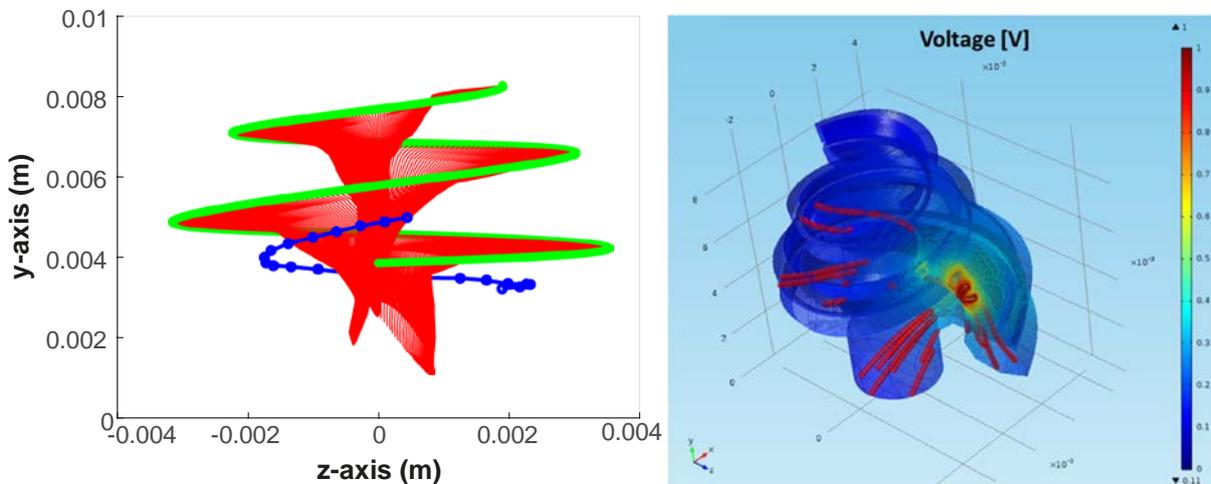
203 Figure 3. Monopolar (*panel A*) and current steering stimulation principle (*panel B*) with the resulting
 204 voltage spread. *Panel C*: Exemplary stimulation cycle for the F120 Sequential, Paired, and Triplet strategies.

205 **2. Excitation Patterns using Sequential, Paired and Triplet**
 206 **Stimulation**

207 The effect of spectral smearing using the F120 Sequential, Paired and Triplet strategies was
 208 first analyzed in simulation using a 3D finite-element model of the electrically-stimulated
 209 cochlea (see Nogueira, Schurzig, Büchner, Penninger, & Würfel, 2016 for details). Figure 4
 210 demonstrates the output from this model as follows.

211 The spread of electric current in the cochlea is simulated in a 3D finite element method (FEM)
 212 from the geometry of the cochlea containing the Scala tympani, Scala vestibuli, Reisner
 213 membrane, basilar membrane, the modiolus and the nerve. The left panel in Figure 4
 214 demonstrates the geometry of the auditory nerve. A spline interpolation of the auditory nerve
 215 compartment was used to create 10,000 nerve fibers along the cochlea. The 3D computer
 216 assisted drawing (CAD) model was generated in Inventor® (Autodesk, San Rafael, CA) and
 217 imported into COMSOL Multiphysics® (COMSOL Inc., Burlington, MA) to generate a
 218 tetrahedral mesh using the general physics algorithm. An electrode carrier with 16 half-band
 219 electrode contacts modelling the HiFocus 1J was created, as shown by the blue array in the left

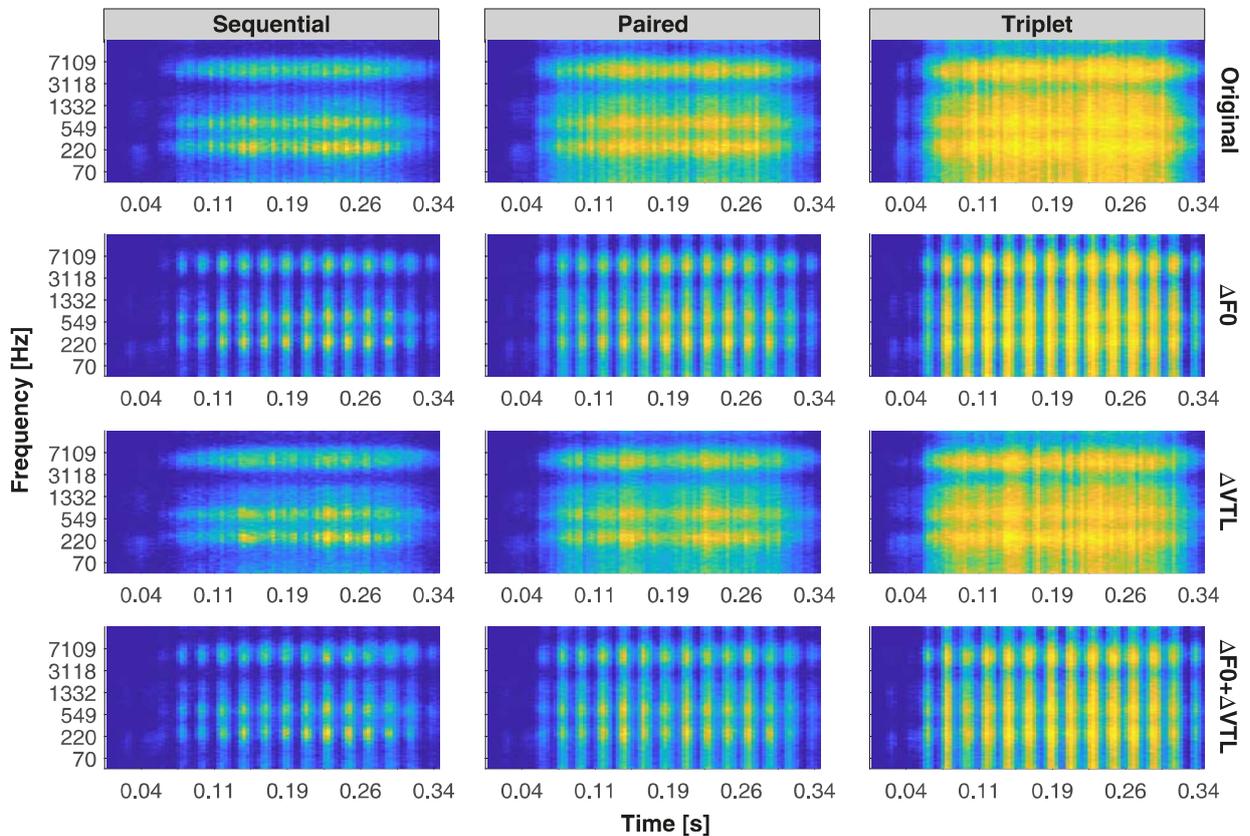
220 panel of Figure 4. The physiology of the auditory nerve fiber was modeled as in Ashida and
 221 Nogueira (2018). The voltage distribution from the FEM, as shown in the right panel of Figure
 222 4, was sampled at the most peripheral node of the nerve section. For each nerve fiber, the
 223 activation function in the most peripheral nerve was computed as in Eq. 4 from Nogueira et al.
 224 (2016). The currents delivered to each electrode across time, also known as electrograms, for
 225 Sequential, Paired and Triplet stimulation were computed using the F120 sound coding strategy
 226 as described in Nogueira et al. (2009). Next the voltage distribution created by the
 227 electrograms was estimated using the 3D voltage distribution model (see right panel of Figure
 228 4). Finally, the neural excitation patterns, i.e. the neural activity across time, were computed
 229 using the nerve fiber model described in Nogueira et al. (2016) which is very similar to the one
 230 presented by Litvak et al. (2007).



232 Figure 4. *Left panel:* Geometry of the auditory nerve (red) with a 16-contact electrode array (blue); *Right*
 233 *panel:* 3D-voltage distribution (electric potential) model based on finite element method. Figure reproduced from
 234 (Nogueira et al., 2016) with permission.

235 German tokens were processed with the Sequential, Paired and Triplet sound coding strategies
 236 using the same levels of stimulation (threshold and most comfortable levels). The stimulation
 237 patterns served as input to the computational model that estimated the excitation patterns.
 238 Figure 5 presents the excitation patterns (number of spikes across fiber number and time) for

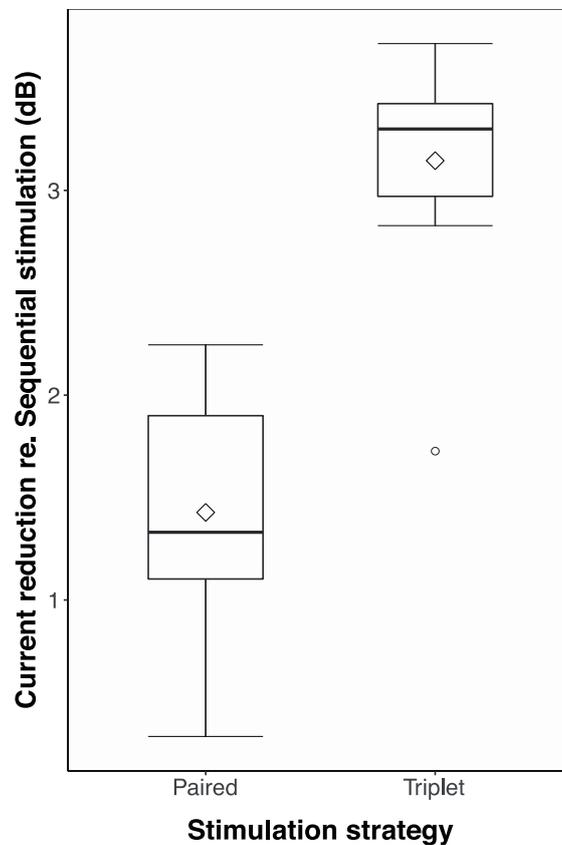
239 the German tokens /da/ and /gɔ/ with the Sequential, Paired and Triplet strategies. Figure 5
 240 demonstrated that increasing the number of parallel channels causes a clear spectral smearing
 241 of the excitation patterns.



242
 243 Figure 5. Neural excitation patterns for the token /da/ using the F120 Sequential (left column), Paired
 244 (middle column) and Triplet (right column) sound coding strategies. The rows indicate different voice cue
 245 manipulations. *Top row*: token spoken by original female speaker; *Second row*: neural excitation pattern after
 246 decreasing F0; *Third row*: neural excitation pattern after elongating VTL; *Bottom row*: neural excitation pattern
 247 after both decreasing F0 and elongating VTL.

248 For each participant in the study, the F120 Sequential was fitted adjusting the most comfortable
 249 level of each electrode individually. Next, the strategy was activated, and the participant asked
 250 to loudness scale the presentation of a CCITT noise at 65 dB SPL free-field. The strategy was
 251 adjusted globally until the participant stated a comfortable loudness. Afterwards, the Paired or
 252 the Triplet sound coding strategies were fitted by globally adjusting the most comfortable level

253 across all electrodes by the same amount starting from the Sequential map fitting while
254 presenting the same noise signal.



255

256 Figure 6. Current reduction in dB when fitting the Paired (left) or Triplet (right) strategies relative to
257 Sequential to achieve the same loudness percept. The boxes extend from the lower to the upper quartile, and the
258 middle line shows the median. The whiskers show the range of the data within 1.5 times the inter quartile range
259 (IQR). Diamond-shaped symbols denote the mean.

260 Figure 6 shows the current reduction in dB for Paired and Triplet relative to Sequential
261 stimulation across all participants recruited in this study. The plot demonstrates that the
262 Sequential strategy requires higher currents than either the Paired or the Triplet strategies to
263 elicit the same loudness percept, and that the Paired strategy requires higher current levels than
264 the Triplet to reach most comfortable loudness, as was demonstrated by Langner et al., (2017).
265 This is mainly due to the electrical interactions between the simultaneously stimulating
266 channels, decreasing the necessary current for the same loudness. These interactions are

267 depending on the number of and the distance between the stimulating channels. The channel
268 stimulation rate was kept constant across strategies by introducing a non-stimulating zero-phase
269 after the end of the second phase of the biphasic pulse (see Figure 3b). This also implies the
270 possibility to reduce power consumption even more, since an increase in the pulse duration
271 requires much lower current levels to achieve the same loudness percept (Shannon, 1985, 1989)
272 due to the resulting additional spread of excitation (McKay & McDermott, 1999). From this
273 analysis, it can be concluded that adding parallel channels causes current smearing which, in
274 turn, causes a reduction in the current levels required to achieve the same loudness percept, thus
275 achieving the proposed current savings.

276 **D. Task 1: F0 and VTL JNDs**

277 **1. Stimuli**

278 The methods for this experiment are largely similar to the ones described in El Boghdady et al.
279 (2019) and identical to those in El Boghdady et al. (in press). Therefore, they are described
280 briefly here. Speech material from the Freiburg monosyllabic word test (Hahlbrock, 1953),
281 which consisted of meaningful German monosyllabic words, were re-recorded for this study
282 from an adult native German female speaker. The voice of the speaker had an estimated average
283 F0 of 233 Hz and VTL of 13.9 cm based on her height (164 cm) using the data from Fitch and
284 Giedd (1999). All recordings were equalized in root mean square (RMS) intensity.

285 Recordings were made in a sound-isolated anechoic chamber at the University Medical Center
286 Groningen, NL, using a RØDE NT1-A microphone mounted on a RØDE SM6 with a pop-
287 shield (RØDE Microphones LLC, CA, USA). The microphone was connected to a PreSonus
288 TubePre v2 amplifier (PreSonus Audio Electronics, Inc., LA, USA) with noise filtering below
289 80 Hz. The amplifier output was recorded through the left channel of a DR-100 MKII TASCAM
290 recorder (TEAC Europe GmbH, Wiesbaden, Germany) at a sampling rate of 44.1 kHz. Seventy-
291 five consonant-vowel (CV) syllables were manually extracted from the recorded words in the

292 corpus, resulting in a list of combinations of the consonants [b, d, f, g, h, k, l, ʃ, m, n, p, ʁ, z, ʒ,
293 t, v, x, ts] and vowels [i:, o:, u:, a, ε, ɪ, ʊ, ɔ, e:].

294 A single trial consisted of concatenating three random CV syllables, with a 50-ms silence in
295 between, to form a triplet of syllables. Within the trial, the same triplet of syllables was
296 presented three times, with a 250 ms silence gap between each presentation. One of these three
297 presentations was processed to have a different voice (lower F0, longer VTL, or both), as
298 indicated by the vectors from the origin of the $[\Delta F0, \Delta VTL]$ plane to the red crosses shown in
299 Figure 1. All three presentations were resynthesized with STRAIGHT (Kawahara & Irino,
300 2005), even when F0 and VTL were not manipulated. The task was to select the triplet that had
301 a different voice with respect to the other two in an adaptive 3-interval, 3-alternative forced
302 choice task (3I-3AFC).

303 **2. Procedure**

304 Following the paradigm used in a number of previous studies (El Boghdady, Başkent, &
305 Gaudrain, 2018; El Boghdady et al., 2019, e.g., in press; Gaudrain & Başkent, 2015, 2018),
306 JNDs in this experiment were measured along three voice vectors, as indicated by the red
307 crosses in Figure 1, using a 2-down 1-up adaptive procedure. This adaptive procedure results
308 in 70.7% correct responses on the psychometric function (Levitt, 1971). A JND measurement
309 consisted of a number of trials: a trial started with the target (voice-manipulated) triplet having
310 a difference of 12 st relative to the other two reference triplets. After the participant's response,
311 a new trial began with a triplet composed of different combinations of syllables than the
312 previous trial. If the participant was able to detect the voice manipulated triplet correctly on two
313 consecutive trials, the voice difference between the reference triplets and the voice-manipulated
314 triplet was reduced by 4 st. Otherwise, if the participant was unable to correctly identify the
315 voice-manipulated triplet, the difference between the reference triplets and the voice-
316 manipulated triplets was increased by the same step size. If the difference between the voice-

317 manipulated and reference triplets became less than twice the step size, the step size was
318 reduced by a factor of $\sqrt{2}$. The procedure terminated after 8 reversals and the JND was
319 calculated as the mean of the last 6 reversals.

320 The JND measurement for each of the three voice vectors was repeated three times per strategy,
321 resulting in a total of 27 experimental conditions (3 voice vectors \times 3 repetitions each \times 3 coding
322 strategies). Experimental conditions were blocked per strategy, meaning that a participant
323 would perform all conditions for a given strategy before switching to the next one, and the order
324 of the strategies was randomized per participant. Participants were blinded to the strategies
325 tested.

326 Training was administered before the beginning of each strategy block with two voice spokes
327 different than those used for data collection: [$\Delta F0 = +5$ st, $\Delta VTL = -7$ st] and [$\Delta F0 = -12$ st,
328 $\Delta VTL = +3.8$ st]. Each training condition was terminated after 6 trials, whether the algorithm
329 had converged or not. Visual feedback was always provided.

330 **E. Task 2: Speech-on-Speech Intelligibility**

331 **1. Stimuli**

332 Stimuli taken from the German HSM sentence test (Hochmair-Desoyer et al., 1997) were used
333 for the SoS intelligibility task, which is composed of 30 lists with 20 sentences taken from
334 everyday speech, including questions. Sentences in this corpus are made up of three to eight
335 words, with a single list containing 106 words in total. Lists 1-19 were used in this experiment
336 and were previously recorded at the MHH from an adult native German female speaker, who
337 had an average F0 of 218 Hz. All recordings were equalized in RMS intensity.

338 Four different masking voices were created as shown in Figure 1: the same talker as the target
339 female [resynthesized with $\Delta F0 = 0$ st, $\Delta VTL = 0$ st], a talker with a lower F0 relative to the

340 target female [$\Delta F0 = -12$ st, $\Delta VTL = 0$ st], a talker with a longer VTL relative to the target
341 female [$\Delta F0 = 0$ st, $\Delta VTL = +3.8$ st], and a talker with both a lower F0 and a longer VTL
342 relative to the target female to obtain a male-like voice [$\Delta F0 = -12$ st, $\Delta VTL = -3.8$ st]. These
343 conditions are referred to as Same Talker, F0, VTL, and F0+VTL, respectively, in the rest of
344 this manuscript. The parameters for F0 and VTL were chosen based on the findings of an earlier
345 study, in which CI users showed reduced SoS intelligibility and comprehension when the voice
346 of the masker was manipulated with parameters taken from the top-right quadrant in Figure 1
347 (El Boghdady et al., 2019). In that study, the authors reasoned that masking voices taken from
348 the lower-left quadrant, as performed in the current study, should be expected to yield a benefit
349 in SoS performance for CI users. This premise was statistically tested in the results section of
350 this experiment.

351 Test sentences were taken from lists 1-8 and 16-19, while maskers were constructed from lists
352 9 and 10. Training sentences were obtained from lists 11, 12, and 13, with one list randomly
353 assigned per strategy. All sentences assigned for constructing the maskers were processed
354 offline before data collection using STRAIGHT, with all combinations of $\Delta F0$ and ΔVTL
355 highlighted above. For the Same Talker condition, the masker sentences were also processed
356 with STRAIGHT, without changing F0 or VTL. All target sentences were not processed with
357 STRAIGHT.

358 Within a trial, the masker sequence started 500 ms before the onset of the target sentence and
359 ended 250 ms after the offset of the target. For the specific $\Delta F0$ and ΔVTL combination within
360 the trial, the masker was constructed from random 1-second-long segments selected from the
361 masker sentences previously processed with STRAIGHT. A raised cosine ramp of 2 ms was
362 applied to the beginning and end of each segment before concatenating them to form the masker
363 sequence. Finally, both the beginning and end of the entire masker sequence were ramped using
364 a 50-ms raised cosine ramp.

365 Target sentences were calibrated at 65 dB SPL, and the intensity of the masker sequence was
366 adjusted relative to that of the target to obtain the required target-to-masker ratio (TMR). The
367 TMRs used for training and data collection in this task were set to +8 dB and +12 dB,
368 respectively, following the protocol of El Boghdady et al. (2019). In that study, the authors
369 demonstrated that a TMR of +8 dB has the potential of capturing group performance in the
370 middle of the psychometric function (away from floor and ceiling effects). The stimuli for all
371 three experiments were sampled at 44.1 kHz, processed, and presented using MATLAB
372 R2014b (The MathWorks, Natick, MA).

373 **2. Procedure**

374 The SoS paradigm for this experiment was based on that used by El Boghdady et al. (2019, in
375 press). A given trial consisted of presenting a single target-masker combination and the
376 participant was asked to repeat what they heard from the target sentence. As in task 1,
377 experimental conditions were blocked per strategy and the order of the strategies was
378 randomized per participant.

379 A short training was provided for each strategy block, with both auditory and visual feedback.
380 During the training phase of a given strategy, 12 sentences were randomly selected from the
381 assigned training list: 6 sentences were presented in quiet, while the remaining 6 were presented
382 with a competing masker. The masker voice used for training was assigned different values for
383 $\Delta F0$ and ΔVTL than those used during data collection (-6 st and +6 st, respectively).

384 Data collection was composed of a total of 240 trials for all three strategy blocks (20 sentences
385 per list \times 4 voice conditions \times 3 strategies) generated offline prior to the beginning of the
386 experiment. The trials within a strategy block were pseudo-randomized. No feedback was
387 provided, and the stimulus was presented once. The participants' responses were scored on a
388 word-by-word basis using a graphical user interface (GUI) programmed in MATLAB.

389 Additionally, the verbal responses were recorded and stored as data files for later offline
390 inspection.

391 Response words were scored in the following fashion: the German HSM sentences includes
392 words that are hyphenated in the corpus, such as ‘Wochen-ende’ (weekend). These words,
393 although written without the hyphen, are hyphenated in the HSM corpus to be scored separately.
394 Only the part repeated by the participant was marked as correct. Additionally, the response
395 word was also considered correct if a participant changed the order of the words in the sentence.

396 A response word was considered incorrect if only a part of the word was repeated for words
397 that are not hyphenated in the HSM corpus, such as saying ‘füllt’ when the word was ‘überfüllt’
398 (crowded). Additionally, confusion of adjective form, e.g. saying ‘keiner’ (‘not any’ as used
399 with a masculine noun) instead of ‘keine’ (‘not any’ as used with a feminine noun), or confusing
400 the Dativ with the Akkusativ article, e.g. confusing ‘der’ with ‘dem’ or ‘den’, was also
401 considered incorrect. Confusion of verb tenses or incorrect verb conjugation was considered
402 incorrect. A total of four scheduled breaks were programmed into the experiment script,
403 however, participants were encouraged to ask for additional breaks whenever they felt
404 necessary.

405 **F. Task 3: Speech-on-Speech Comprehension**

406 **1. Stimuli**

407 The voice conditions for the masker in this experiment were the same as defined in experiment
408 1. The masker sequence was created as described in experiment 1 from lists 9 and 10 from the
409 HSM material. Target sentences were based on German translations of the Dutch sentence
410 verification task (SVT) developed by Adank and Janse (2009) and designed to measure
411 sentence comprehension accuracy and speed (RT). This corpus is composed of 100 pairs of
412 sentences, with each pair composed of a true (e.g. *Beyers bouwen dammen in de rivier* [Beavers

413 build dams in the river]) and false version (e.g *Bevers grooien in een moestuin* [Beavers grow
414 in a vegetable patch]). All sentences are grammatically and syntactically correct.

415 Translation from Dutch to German and the evaluation was performed thoroughly by three
416 independent native German speakers: two of those speakers were also fluent in Dutch, while
417 the third had sufficient knowledge of the language (see El Boghdady et al., in press, for a full
418 description of the translation procedure). One sentence pair lost its meaning when translated to
419 German and was discarded from the translations, resulting in 99 true-false sentence pairs. The
420 additional four sentence pairs introduced by El Boghdady et al. (2019) for training purposes
421 were translated to German as well.

422 Recordings were made in the same manner and using the same setup as those described in task
423 1. Recordings were taken from an adult native German female speaker, with an average F0 of
424 180 Hz, and an estimated VTL of about 14.1 cm following the method provided by Ives et al.
425 (2005) and the data from Fitch and Giedd (1999).

426 **2. Procedure**

427 Following the paradigm in previous studies for the SVT (Adank & Janse, 2009; El Boghdady
428 et al., in press; Pals, Sarampalis, Beynon, Stainsby, & Başkent, 2016), participants were asked
429 if the target sentence was true (labeled ‘WAHR’) or false (labeled ‘UNWAHR’) by pressing
430 the corresponding button on a button-box as quickly and accurately as possible within a time
431 window of 6 seconds. The window was larger than the one used in Pals et al. (2016), to
432 accommodate the CI users and not prime them to guess on most trials. If the time window was
433 exceeded, the response was recorded as a no-response, and the next stimulus was presented.
434 RTs were measured relative to the offset of the resolving word in the stimulus as was done by
435 El Boghdady et al., (in press).

436 As was done in tasks 1 and 2, trials were also blocked per strategy, with the starting strategy
437 randomized across participants. A short training was provided at the beginning of each strategy
438 block. Twelve fixed sentence pairs were assigned for training and were excluded from data
439 collection. Out of these pairs (24 true-false sentences), four true and four false sentences were
440 randomly picked and assigned to the training block of each strategy. No true-false pair was
441 assigned to the same training block.

442 In each training block, 2 true and 2 false sentences were first presented without a competing
443 masker, followed by the remaining 2 true and 2 false sentences, which were presented with a
444 competing masker. This masker also had the same voice parameters as those of the training
445 masker voice used in task 2 and at the same training TMR of +12 dB. Both audio and visual
446 feedback was provided: participants were shown if the sentence was true or false, and the
447 sentence was shown on the screen while the whole stimulus was replayed through the
448 loudspeaker.

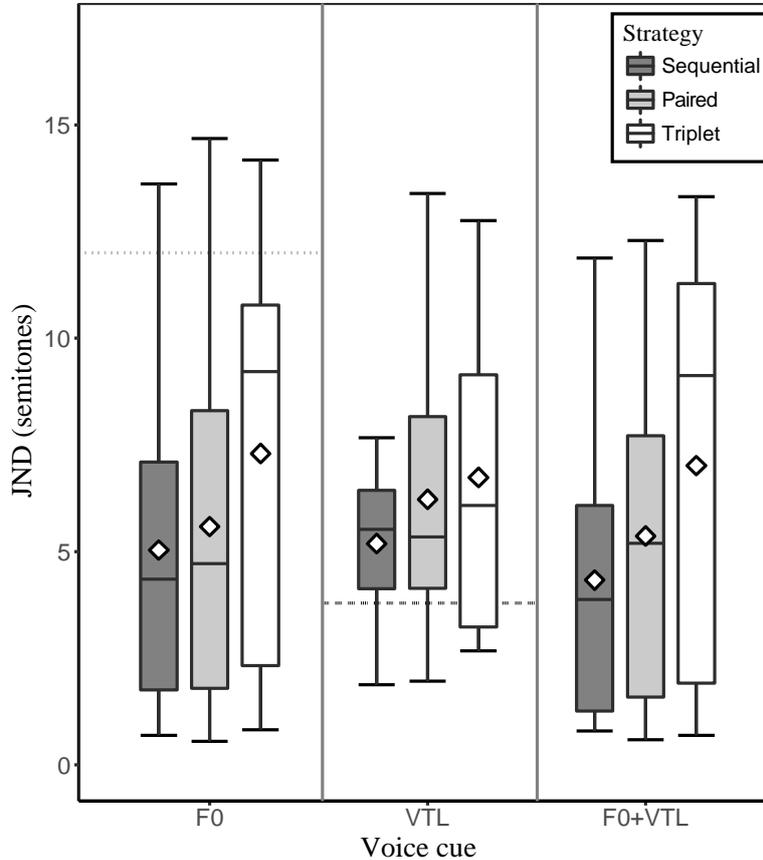
449 The remaining sentences not used for training were used for data collection. These sentences
450 were distributed among the number of conditions tested (4 masker voice conditions \times 3
451 strategies), and no true-false pair was assigned to the same condition. All stimuli were generated
452 offline for all three strategy blocks and pseudo-randomized within each block. During data
453 collection, no feedback was given.

454 **II. RESULTS AND DISCUSSION**

455 All data were analyzed using R (version 3.3.3, R Foundation for Statistical Computing, Vienna,
456 Austria, R Core Team, 2017), and regression models were implemented using the *lme4* package
457 (version 1.1-15, Bates, Mächler, Bolker, & Walker, 2015). When multiple comparisons were
458 carried out, as in the case of the post-hoc analyses, a false-discovery rate (FDR) correction
459 (Benjamini & Hochberg, 1995) was then applied to these *p*-values obtained from the multiple
460 comparisons.

461 **A. Task 1: Effect of channel interaction on F0 and VTL**

462 **JNDs**



463
 464 Figure 7. JND distributions for F0, VTL, and F0+VTL cues obtained under each stimulation strategy:
 465 Sequential (dark grey boxes), Paired (light grey boxes), and Triplet (white boxes). *F0*: JNDs obtained along the
 466 negative F0 axis (lowering F0). *VTL*: JNDs obtained along the positive VTL axis (elongating VTL). *F0+VTL*:
 467 JNDs obtained along the diagonal with the combination F0 = -12 st, VTL = +3.8 st, simulating a male voice. The
 468 boxplot statistics are as indicated in Figure 6. The horizontal dashed line indicates a VTL difference of 3.8 st as
 469 used in the masker setup of tasks 2 and 3. The horizontal dotted line indicates an F0 difference of 12 st as used in
 470 the masker setup of tasks 2 and 3.

471 Figure 7 shows the JND distributions across all participants obtained for each voice cue, and
 472 indicates, as expected, a trend of worsening (increasing) JNDs as the amount of channel
 473 interaction increases (going from Sequential stimulation to Paired to Triplet). To investigate the
 474 general effect of channel interaction (stimulation strategy) on voice cue JNDs, a linear mixed-

475 effects model (LMM) was fitted to the log-transformed JNDs. This transformation was
476 performed because the raw JNDs are bounded by zero and thus do not follow a normal
477 distribution. The model was defined with strategy and voice cue (F0, VTL, and F0+VTL), along
478 with their interaction, as the fixed-effect predictors. Interaction effects were included in the
479 model to test whether the effect of strategy changes for different voice cues. Differences in
480 baseline performance between participants, in addition to variations in the effect of strategy
481 from one participant to the other, were accounted for in the linear model as random effects. To
482 quantify the general effect of strategy on JNDs, a one-way type III repeated-measures analysis
483 of variance (ANOVA) was applied to the aforementioned linear model and revealed a
484 significant general effect of strategy on JNDs [$F(2,11.21) = 4.70, p = 0.03$], but no significant
485 differences in JNDs between the different voice cues [$F(2,13.35) = 1.98, p = 0.18$]. The
486 interaction effect between strategy and voice cue was also found to be non-significant [$F(4,55)$
487 $= 0.91, p = 0.47$].

488 A similar LMM (including only a random intercept per participant as the random effect) was
489 applied to each type of JND separately (F0, VTL, or F0+VTL) to study how stimulation strategy
490 (channel interaction) affects each individual voice cue. A similar ANOVA to the one applied
491 on the general model above was also applied here for each model separately, and p -values were
492 then adjusted for multiple comparisons using the False Discovery Rate (FDR) method
493 (Benjamini & Hochberg, 1995). These ANOVAs revealed that the general effect of strategy
494 observed in the general model arose from a significant effect of strategy on F0 JNDs [$F(2,22)$
495 $= 4.59, p = 0.03$] and F0+VTL JNDs [$F(2,22) = 4.56, p = 0.03$], but not on VTL JNDs [$F(2,22)$
496 $= 1.23, p = 0.31$].

497 The post-hoc analyses of these tests revealed that F0 JNDs increased by about 1.44 st as the
498 strategy changed from Sequential to Triplet [$\beta = 0.36, SE = 0.13, t(22) = 2.87, p = 0.03$], but
499 did not seem to be affected by Paired stimulation [$\beta = 0.07, SE = 0.13, t(22) = 0.59, p = 0.56$].

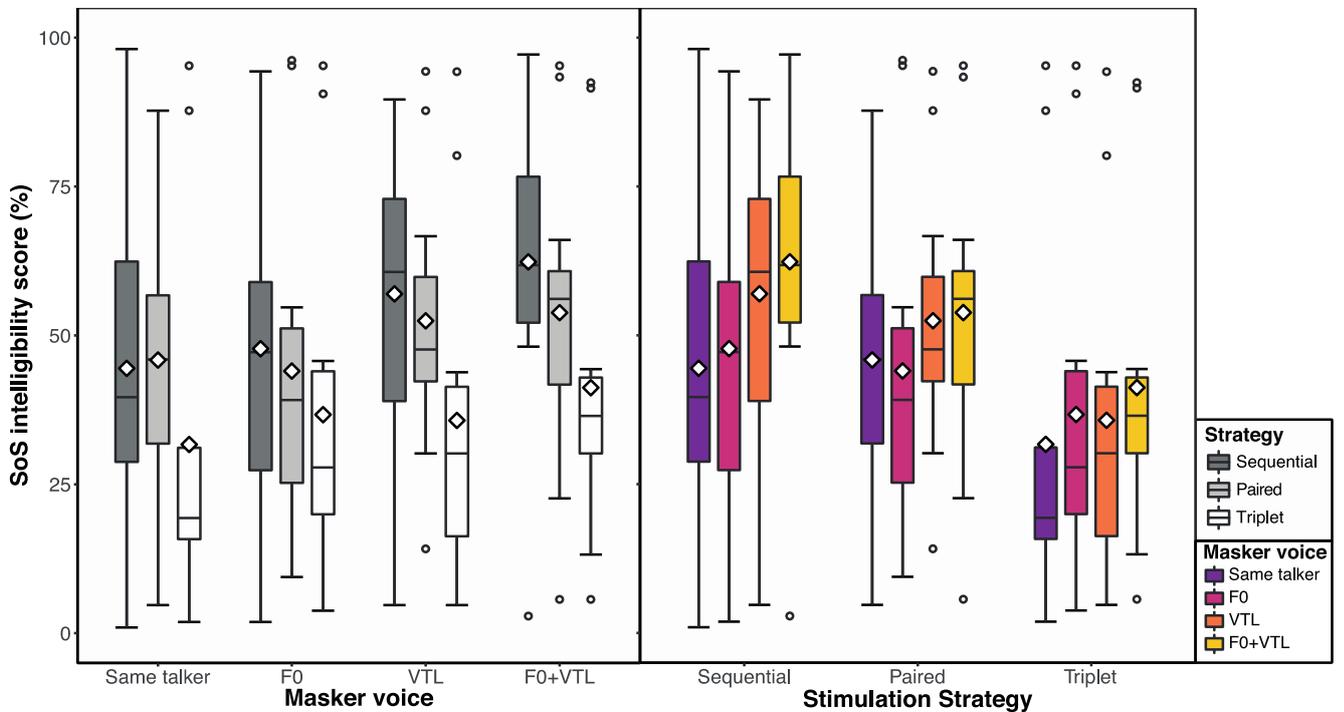
500 On the contrary, VTL JNDs were neither affected by Paired [$\beta = 0.12$, $SE = 0.12$, $t(22) = 1.01$,
501 $p = 0.39$] nor by Triplet stimulation [$\beta = 0.19$, $SE = 0.12$, $t(22) = 1.54$, $p = 0.21$] compared to
502 Sequential. Finally, the participants' JNDs to differences along both F0 and VTL (F0+VTL
503 condition) also significantly increased (worsened) by about 1.35 st when the stimulation
504 strategy was changed from Sequential to Triplet [$\beta = 0.37$, $SE = 0.12$, $t(22) = 3.02$, $p = 0.03$]
505 but not from Sequential to Paired [$\beta = 0.19$, $SE = 0.12$, $t(22) = 1.57$, $p = 0.21$].

506 Taken together, these results indicate that when mild channel interaction exists, as was the case
507 when Paired stimulation was compared to Sequential, sensitivity to voice cue differences was
508 not significantly affected. However, as the channel interaction dramatically increased, as was
509 the case with Triplet stimulation, sensitivity to voice cue differences was reduced. Because no
510 significant interaction effect between stimulation strategy and voice cue was observed in the
511 overall model, the effect of strategy should not be expected to differ for each voice cue. The
512 fact that post-hoc analyses revealed no significant effect of strategy on VTL JNDs may have
513 arose from the relatively smaller differences in VTL JNDs across all three strategies compared
514 to the F0 differences, even though a trend for worsening VTL JNDs could be observed. In an
515 earlier study with vocoders, Gaudrain and Başkent (2015) have shown that when the number
516 of effective spectral channels was sufficient, increasing channel interaction (shallower vocoder
517 filters) did not lead to a significant worsening of VTL JNDs. Thus, an alternative explanation
518 for these findings could be that the participants tested in the current study already had sufficient
519 effective spectral channels which might have mitigated the detrimental effects of increased
520 channel interaction.

521 A second observation concerns the effect of channel interaction on F0 JNDs. Because F0
522 information is encoded in both spectral and temporal cues (Carlyon & Shackleton, 1994), it was
523 expected that the representation of F0 should have been robust to spectral degradations
524 introduced by increased channel interaction. However, F0 cues were shown to be impaired by

525 increased channel interaction, indicating that the temporal aspect of these cues could not
 526 provide adequate F0 information for the CI listeners to reach the same JNDs as in the condition
 527 of minimal channel interaction (Sequential stimulation). These findings indicate that an
 528 adequate spectral resolution in the implant would be crucial for transmitting both F0 and VTL-
 529 related cues.

530 **B. Task 2: Effect of channel interaction on SoS**
 531 **intelligibility**



532
 533 Figure 8. *Left panel:* SoS intelligibility score distribution across participants under each stimulation
 534 strategy (*Sequential:* dark grey; *Paired:* light grey; *Triplet:* white) for each masker voice condition. *Right panel:*
 535 same as left panel but demonstrating the effect of changing the masker voice for each stimulation strategy. *Same*
 536 *talker:* the condition when the target and masker were the same female speaker ($\Delta F0 = 0$ st, $\Delta VTL = 0$ st). *F0:* the
 537 condition when the masker had a lower F0 ($\Delta F0 = -12$ st, $\Delta VTL = 0$ st) relative to that of the target speaker. *VTL:*
 538 the condition when the masker had a longer VTL ($\Delta F0 = 0$ st, $\Delta VTL = +3.8$ st) relative to that of the target.
 539 *F0+VTL:* the condition when the masker had both a lower F0 and a longer VTL ($\Delta F0 = -12$ st, $\Delta VTL = +3.8$ st)
 540 relative to those of the target. The boxplot statistics are the same as described in Figure 6.

541 Figure 8 shows the distribution of SoS intelligibility scores across participants for each masker
542 voice condition under each stimulation strategy. The scores in this figure were computed as the
543 percentage of correctly repeated words out of the total number of words presented per condition.
544 The data demonstrates that even though there is a large variability in performance across the CI
545 participants for each stimulation strategy (left panel), there appears to be a trend for decreasing
546 SoS intelligibility scores as the amount of channel interaction increases (going from Sequential
547 stimulation to Paired to Triplet). In addition, the representation of the data in the right panel
548 reveals that the degree of benefit in SoS intelligibility scores obtained from changing the masker
549 voice relative to that of the target seems to decrease as the amount of channel interaction
550 increases.

551 The binary per-word scores (0: incorrect; 1: correct) were modelled using logistic regression as
552 implemented by a generalized linear mixed-effects model (GLMM) with a logit link function.
553 The logistic regression model was fit to the binary per-word score with strategy and masker
554 voice, along with their interaction, as the fixed-effects. The interaction between stimulation
555 strategy and masker voice was included to test for the significance of the effect observed in the
556 right panel of Figure 8, in which the degree of benefit in SoS intelligibility scores obtained from
557 changing the masker voice seems to diminish as the amount of channel interaction increases.
558 The GLMM was also defined to estimate a random intercept per participant to account for
559 differences in baseline performance across participants. Additionally, random effects for
560 strategy per participant and masker voice per participant were also included in the model to
561 account for variations in the effect of strategy and masker voice on SoS intelligibility across
562 participants.

563 As with the analyses of the JND task, an ANOVA (car package; Fox & Weisberg, 2011) was
564 applied to the GLMM to test for the global effect of strategy, masker voice, and their interaction
565 on the SoS intelligibility scores. Because this ANOVA is applied to a logistic regression model,

566 the output is a table of chi-squared (χ^2) tests performed on the fixed-effects of the model instead
567 of the traditional F -test statistics. The ANOVA revealed a significant effect of stimulation
568 strategy [$\chi^2(2) = 27.29, p < 0.0001$], masker voice [$\chi^2(3) = 36.32, p < 0.0001$], and their
569 interaction [$\chi^2(6) = 37.34, p < 0.0001$].

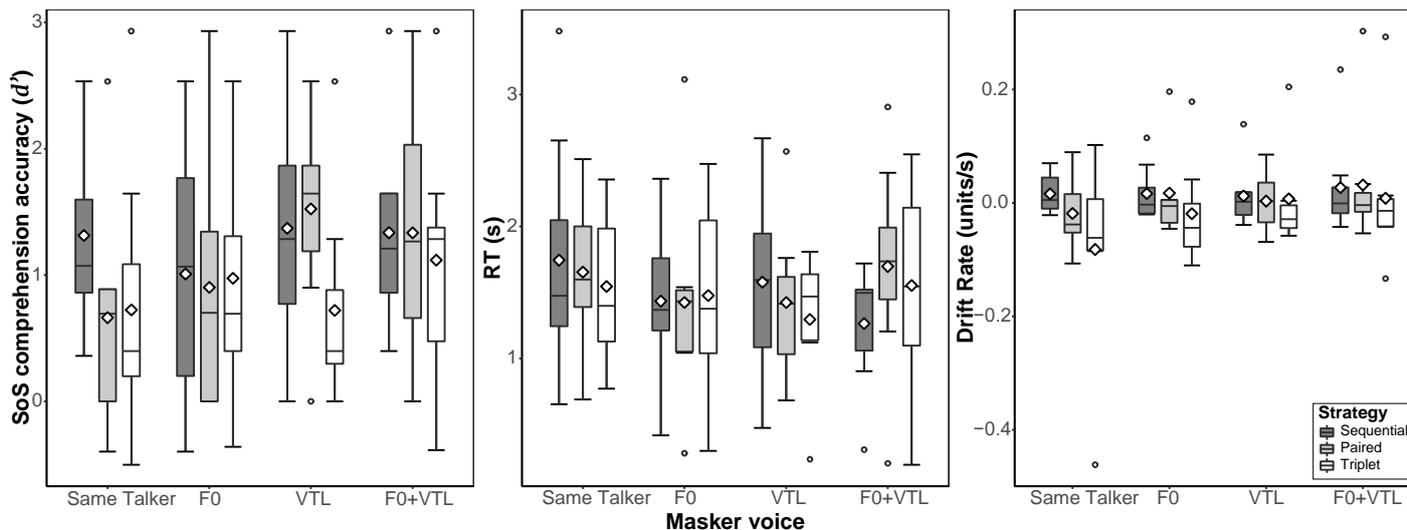
570 A post-hoc analysis was conducted using an ANOVA applied to the logistic regression model
571 for the effect of strategy under each voice cue separately with FDR correction applied to the p -
572 values. This analysis revealed that SoS intelligibility decreased as a function of increasing
573 channel interaction for the Same Talker condition [$\chi^2(2) = 9.34, p = 0.01$], F0 condition [$\chi^2(2)$
574 = 8.99, $p = 0.01$], VTL condition [$\chi^2(2) = 26.39, p < 0.0001$], and F0+VTL condition [$\chi^2(2) =$
575 34.69, $p < 0.0001$] (see left panel of Figure 8). These effects seemed to arise from the significant
576 reduction in SoS intelligibility under Triplet stimulation compared to Sequential for most voice
577 conditions [Same Talker: $\beta = -0.68, SE = 0.23, z = -2.92, p = 0.009$; F0: $\beta = -0.53, SE = 0.28, z$
578 = -1.91, $p = 0.11$; VTL: $\beta = -1.00, SE = 0.26, z = -3.81, p < 0.001$; F0+VTL: $\beta = -1.03, SE =$
579 0.20, $z = -5.16, p < 0.0001$], but not between Paired and Sequential stimulation as obtained from
580 the coefficients of the logistic regression model [Same Talker: $\beta = 0.05, SE = 0.22, z = 0.23, p$
581 = 0.82; F0: $\beta = -0.10, SE = 0.22, z = -0.44, p = 0.75$; VTL: $\beta = -0.12, SE = 0.26, z = -0.45, p =$
582 0.75; F0+VTL: $\beta = -0.38, SE = 0.24, z = -1.59, p = 0.18$]. Consistent with the observations made
583 from the JND task, a reduction in SoS intelligibility was observed with increasing channel
584 interaction for all voice conditions. Thus, as channel interaction increases, spectral features that
585 are important for both voice cue perception and SoS intelligibility appear to be degraded.

586 The significant interaction effect from the global ANOVA indicates that the benefit in SoS
587 intelligibility obtained from changing the masker voice cues relative to those of the target was
588 affected by the amount of channel interaction: as the channel interaction increased (going from
589 Sequential stimulation to Paired to Triplet), the benefit obtained from the voice differences
590 between masker and target speakers (going from Same Talker to F0 to VTL and then to

591 F0+VTL) decreased significantly (see right panel of Figure 8). In the Triplet case, the SoS
 592 intelligibility score for the baseline condition (Same Talker) was severely reduced compared to
 593 the same condition under Sequential stimulation. In addition, the largest benefit obtained from
 594 the condition F0+VTL under Triplet stimulation is almost the same as the mean intelligibility
 595 score for the same talker condition under either Sequential or Paired stimulation.

596 These findings reveal that substantial channel interaction may sufficiently degrade the signal to
 597 the extent that a benefit in SoS intelligibility from voice cue differences between two concurrent
 598 speakers may be impaired. Moreover, consistent with what has been observed in the JND task,
 599 CI participants appear to withstand mild channel interaction without a significant drop in their
 600 performance levels. However, as the channel interaction becomes more substantial, as is the
 601 case when Triplet stimulation is applied, overall SoS intelligibility scores start decreasing
 602 dramatically.

603 C. Task 3: Effect of channel interaction on SoS 604 comprehension accuracy and response times



605
 606 Figure 9. SoS comprehension accuracy in d' (left panel), RT (middle panel), and drift rate (right panel) for
 607 each masker voice condition under each stimulation strategy. Boxplot statistics and description of conditions are
 608 the same as those described in the caption of Figure 6.

609 Figure 9 shows the SoS comprehension performance for each masker voice under each
610 stimulation strategy. The right panel shows the effect of strategy on SoS comprehension
611 accuracy converted to the sensitivity measure d' , computed as the ratio between the hit rate and
612 the false alarm rate (Green & Swets, 1966). The d' measure was used instead of percent correct
613 because the d' is unbiased to a participant's particular preference for one response at the expense
614 of the other. The large inter-participant variability appears to dilute the effect of strategy. As
615 with the analyses applied to the data of the previous two tasks, an LMM was fit to the d' data
616 with strategy, masker voice, and their interaction as the fixed effects, and a random intercept
617 per participant. Adding random slopes for the effect of strategy per participant and masker voice
618 per participant did not improve the model fit to the data [$\chi^2(20) = 15.58, p = 0.74$], and was
619 thus not included in the final LMM. An ANOVA similar to that applied to the LMM in the JND
620 task was also applied to the LMM modeling the d' data and revealed no effect of strategy
621 [$F(2,77) = 2.68, p = 0.07$], masker voice [$F(3,77) = 1.82, p = 0.15$], or their interaction [$F(6,77)$
622 $= 1.20, p = 0.31$] on the d' accuracy scores.

623 The middle panel of Figure 3 shows the RT distributions obtained for each masker voice
624 condition under each of the three stimulation strategies. Again, because of the large inter-
625 participant variability, the effect of strategy on RTs is not evident. Because the RTs considered
626 were those corresponding to only the correct responses, the number of RT data points differed
627 across participants and conditions, which rendered the use of an ANOVA inappropriate.
628 Additionally, the RT distributions per participant per condition were largely positively skewed.
629 For these reasons, a GLMM with an inverse Gaussian distribution and inverse link function was
630 fit to the RT data, as was suggested by Lo and Andrews (2015), and as was carried out by El
631 Boghdady et al. (2019, in press). The GLMM best fitting the RT data included strategy, masker
632 voice, and their interaction as the fixed-effects, in addition to random intercepts per participant.
633 Including a random slope for strategy and masker voice per participant did not improve the
634 overall model fit [Akaike information criterion (AIC) = 4213.03 and Bayesian information

635 criterion (BIC) = 4362.18 for the model with random slopes versus AIC = 4205.78 and BIC =
636 4267.19 for the model without random slopes]. An ANOVA applied to the GLMM best fitting
637 the RT data did not reveal either any effect of strategy [$\chi^2(2) = 0.006, p = 0.997$], masker voice
638 [$\chi^2(3) = 0.049, p = 0.997$], or their interaction [$\chi^2(6) = 0.167, p = 0.9999$] on RTs.

639 In this task, the no effect of strategy could be observed either for SoS comprehension accuracy
640 or RTs when each measure was considered in isolation. Qualitatively, this implies that
641 participants may be compromising accuracy for speed or vice versa, and that these response
642 strategies differ per condition. Consider, for example, the d' accuracy scores and RT data for
643 the VTL condition. It appears that as participants give less accurate scores as the channel
644 interaction increases, they also give these responses faster. However, this response strategy
645 seems to change for the condition F0+VTL. In that condition, as channel interaction increases,
646 participants also give less accurate responses, but they do so at slower speeds.

647 Thus, to address this speed-accuracy trade-off, a more unified measure of performance called
648 the drift rate is helpful (for a review, see Ratcliff, Smith, Brown, & McKoon, 2016), and would
649 be more suitable for assessing changes in difficulty level across the different conditions
650 (Wagenmakers, Van Der Maas, & Grasman, 2007). The drift rate, as shown in the right panel
651 of Figure 9, estimates the participants' accuracy rate for each condition, and was computed
652 using the EZ-drift diffusion model (EZ-DDM; Wagenmakers et al., 2007), which is a simplified
653 version of the full model proposed by Ratcliff (1978). It was not possible to fit full diffusion
654 models, such as that provided in the R package diffIRT (Molenaar, Tuerlinckx, van der Maas,
655 & others, 2015) to the data from this task because the nature of the paradigm used introduced
656 entries with missing data, as described in the methods section. In this situation, the simplified
657 EZ-DDM model was more appropriate.

658 The EZ-DDM makes three assumptions about the data: 1) the RT distributions are positively
659 skewed for each condition (strategy and masker voice); 2) There are no differences between the
660 RT distributions of correct and incorrect responses for each participant under each condition;

661 3) No significant interaction should be present between response accuracy and stimulus
662 category (true/false categories). Following the method proposed by Wagenmakers et al. (2007)
663 for checking whether these assumptions are met by the data, the check performed on the first
664 assumption revealed that the RT distributions were positively skewed.

665 For assumptions 2 and 3, because they were required to be checked for each participant under
666 every condition, there were a few participants who failed the checks for a number of conditions,
667 as was also the case with the data analyzed by Wagenmakers et al. (2007). For assumption 2,
668 P06 failed this check for 2 conditions, P07 and P08 failed this check for one condition, and P10
669 and P11 failed this check for 4 conditions. This indicates that for these conditions, the
670 participants may have had systematically slower or faster error responses compared to correct
671 responses.

672 For assumption 3, only P07, P08, P10, and P11 failed this check for one condition. This
673 indicates that for this condition, P07, P08, P10, and P11 may have had some bias to classify a
674 stimulus as true or false. Nonetheless, the EZ-DDM was still applied here to obtain an
675 approximation for the drift rate. This was motivated by the fact that the sample data used by
676 Wagenmakers et al. also violated the aforementioned assumptions to a larger degree than the
677 data presented in the current manuscript, however, Wagenmakers et al. demonstrated that the
678 EZ-DDM was still able to provide reasonable estimates to the drift rate that were in line with
679 those obtained from the full diffusion model.

680 An LMM was fit to the drift rate data, with strategy, masker voice, and their interaction as fixed
681 effects, and with random intercepts estimated per participant as the random effect. Attempting
682 to include a random slope for strategy per participant and masker voice per participant yielded
683 a non-converging model, and thus were not included in the final LMM. An ANOVA applied to
684 the final LMM revealed a significant effect of strategy [$F(2,70.21) = 4.30, p = 0.02$] and masker
685 voice [$F(3,70.15) = 3.11, p = 0.03$] on the drift rate, but not of the interaction term on the drift
686 rate [$F(3,70.10) = 0.84, p = 0.54$]. This indicates that as the channel interaction increases, and

687 as the voice difference between masker and target increases, the accuracy rate on the SVT task
688 appears to decrease, which is in line with the results observed in task 2.

689 **III. CONCLUSION**

690 This study investigated whether increasing channel interaction as a result of simultaneously
691 stimulating multiple channels in the CI would lead to a reduced sensitivity to F0 and VTL cues
692 (task 1), and correspondingly, reduced SoS intelligibility and comprehension performance
693 (tasks 2 and 3). The data from task 1 — JND — revealed that, in line with what was expected,
694 increasing channel interaction significantly reduced CI users' sensitivity to voice cues (both
695 spectral and temporal features), as demonstrated by the main effect of stimulation strategy in
696 addition to a lack of interaction effect between voice cue and stimulation strategy.

697 The data from task 2 — SoS intelligibility — demonstrated an effect of channel interaction, a
698 benefit from voice differences between target and masker speakers, and a significant interaction
699 effect between these two factors. Compared to Sequential stimulation, increasing the channel
700 interaction was shown to impair SoS intelligibility scores only for Triplet stimulation but not
701 for Paired stimulation. This indicates that for mild cases of channel interaction baseline SoS
702 intelligibility could still be maintained. However, for more extreme cases of channel interaction,
703 as in the case of Triplet stimulation, SoS intelligibility scores become severely degraded. In
704 addition, the lack of detrimental effect of Paired stimulation on voice cue sensitivity and SoS
705 intelligibility provides evidence that parallel stimulation could be utilized as a method for
706 reducing power in CIs without impairing performance on tasks relying on voice cue perception.

707 The voice parameters for F0 and VTL assigned for the maskers in this study (starting from a
708 female voice and approaching a male-like voice) yielded a benefit in SoS intelligibility. In a
709 previous study (El Boghdady et al., 2019), the authors demonstrated that voice parameters taken
710 from the top-right quadrant of the $[\Delta F0, \Delta VTL]$ plane (towards child-like voices) failed to
711 provide release from masking for CI users, even though the differences between those child-

712 like voices and the reference female speaker were larger than those between the male-like
713 voices and the reference female speaker in the current study. Taken together, these data indicate
714 that CI users may benefit differently from voice cue differences depending on which speaker
715 space they cover. However, this benefit from voice differences between target and masker is
716 reduced as the amount of channel interaction increases, as was demonstrated by the significance
717 of the interaction effect observed between stimulation strategy and voice cue. This means that
718 as channel interaction becomes substantial, CI listeners may not be able to benefit from voice
719 cue differences between competing talkers in SoS scenarios.

720 The data from task 3 — SoS comprehension — also corroborated the findings from the previous
721 two tasks regarding the effect of channel interaction. Although comprehension accuracy and
722 RT measures revealed no effect of either channel interaction or voice cue, the drift rate measure
723 was able to demonstrate a detrimental, albeit small, effect of increased channel interaction and
724 masker voice. These findings support the idea that drift rate as a combined measure of
725 comprehension accuracy and speed may provide insight into the data that may not be initially
726 visible in either accuracy or RT measures alone.

727 The findings from this study highlight the importance of spectrotemporal resolution when
728 performing tasks that depend on voice-cue perception. This raises the question of whether CIs
729 could be fitted with the goal of mitigating the effect of decreased spectrotemporal resolution
730 that may arise from channel interaction. Several studies (e.g., Di Nardo, Scorpecci,
731 Giannantonio, Cianfrone, & Paludetti, 2011; El Boghdady et al., 2018; Fitzgerald, Sagi,
732 Morbiwala, Tan, & Svirsky, 2013; Fu & Shannon, 1999; Grasmeyer, Verschuur, & Batty, 2014;
733 Leigh, Henshall, & McKay, 2004; McKay & Henshall, 2002, 2002; Omran, Lai, & Dillier,
734 2011) have proposed that optimizing the frequency-to-electrode allocation map could have the
735 potential to address the limited spectral resolution in the implant. More specifically, using
736 vocoder simulations, El Boghdady et al. (2018) have shown that the frequency-to-electrode

737 allocation map could have a direct influence on VTL JNDs, and that the frequency mapping, if
738 optimally fitted, could help reduce the detrimental effects of channel interaction and frequency
739 mismatch in the cochlea on VTL JNDs. These studies help to pave the way for investigating
740 whether the CI parameters (such as the frequency allocation map) or signal processing could be
741 optimized in a way to improve both SoS perception and the sensitivity to voice cues.

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760 REFERENCES

- 761 Adank, P., & Janse, E. (2009). Perceptual learning of time-compressed and natural fast speech.
762 *The Journal of the Acoustical Society of America*, 126(5), 2649–2659. doi:
763 10.1121/1.3216914
- 764 Ashida, G., & Nogueira, W. (2018). Spike-conducting integrate-and-fire model. *ENeuro*, 5(4).
765 doi: 10.1523/ENEURO.0112-18.2018
- 766 Başkent, D., Gaudrain, E., Tamati, T. N., & Wagner, A. (2016). Perception and psychoacoustics
767 of speech in cochlear implant users. In *Scientific Foundations of Audiology:
768 Perspectives from Physics, Biology, Modeling, and Medicine* (pp. 285–319). San Diego,
769 CA: Plural Publishing, Inc.
- 770 Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models
771 Using lme4. *Journal of Statistical Software*, 67(1), 1–48. doi: 10.18637/jss.v067.i01
- 772 Benjamini, Y., & Hochberg, Y. (1995). Controlling the False Discovery Rate: A Practical and
773 Powerful Approach to Multiple Testing. *Journal of the Royal Statistical Society. Series
774 B (Methodological)*, 57(1), 289–300.
- 775 Boëx, C., de Balthasar, C., Kós, M.-I., & Pelizzone, M. (2003). Electrical field interactions in
776 different cochlear implant systems. *The Journal of the Acoustical Society of America*,
777 114(4), 2049–2057. doi: 10.1121/1.1610451
- 778 Bonthuis, M., van Stralen, K. J., Verrina, E., Edefonti, A., Molchanova, E. A., Hokken-
779 Koelega, A. C., ... Jager, K. J. (2012). Use of national and international growth charts
780 for studying height in European children: Development of up-to-date European height-
781 for-age charts. *PloS One*, 7(8), e42506.

- 782 Büchner, A., Frohne, C., Battmer, R.-D., & Lenarz, T. (2005). Investigation of stimulation rates
783 between 500 and 5000 pps with the Clarion 1.2, Nucleus CI24 and Clarion CII devices.
784 *Cochlear Implants International*, 6(S1), 35–37. doi: 10.1002/cii.280
- 785 Carlyon, R. P., & Shackleton, T. M. (1994). Comparing the fundamental frequencies of
786 resolved and unresolved harmonics: Evidence for two pitch mechanisms? *The Journal*
787 *of the Acoustical Society of America*, 95(6), 3541–3554. doi: 10.1121/1.409971
- 788 Chiba, T., & Kajiyama, M. (1941). *The vowel: Its nature and structure*. Tokyo: Tokyo-
789 Kaiseikan.
- 790 Cullington, H. E., & Zeng, F.-G. (2008). Speech recognition with varying numbers and types
791 of competing talkers by normal-hearing, cochlear-implant, and implant simulation
792 subjects a. *The Journal of the Acoustical Society of America*, 123(1), 450–461. doi:
793 10.1121/1.2805617
- 794 De Balthasar, C., Boex, C., Cosendai, G., Valentini, G., Sigrist, A., & Pelizzone, M. (2003).
795 Channel interactions with high-rate biphasic electrical stimulation in cochlear implant
796 subjects. *Hearing Research*, 182(1), 77–87. doi: 10.1016/S0378-5955(03)00174-6
- 797 Di Nardo, W., Scorpecci, A., Giannantonio, S., Cianfrone, F., & Paludetti, G. (2011). Improving
798 melody recognition in cochlear implant recipients through individualized frequency
799 map fitting. *European Archives of Oto-Rhino-Laryngology*, 268(1), 27–39. doi:
800 10.1007/s00405-010-1335-7
- 801 El Boghdady, N., Başkent, D., & Gaudrain, E. (2018). Effect of frequency mismatch and band
802 partitioning on vocal tract length perception in vocoder simulations of cochlear implant
803 processing. *The Journal of the Acoustical Society of America*, 143(6), 3505–3519. doi:
804 10.1121/1.5041261

- 805 El Boghdady, N., Gaudrain, E., & Bařkent, D. (2019). Does good perception of vocal
806 characteristics relate to better speech-on-speech perception in cochlear implant users?
807 *The Journal of the Acoustical Society of America*, 145(1), 417–439. doi:
808 10.1121/1.5087693
- 809 El Boghdady, N., Langner, F., Gaudrain, E., Bařkent, D., & Nogueira, W. (in press). Effect of
810 spectral contrast enhancement on speech-on-speech intelligibility and voice cue
811 sensitivity in cochlear implant users. *Ear and Hearing*.
- 812 Fant, G. (1960). Acoustic theory of speech perception. *Mouton, The Hague*.
- 813 Fitch, W. T., & Giedd, J. (1999). Morphology and development of the human vocal tract: A
814 study using magnetic resonance imaging. *The Journal of the Acoustical Society of*
815 *America*, 106(3), 1511–1522. doi: 10.1121/1.427148
- 816 Fitzgerald, M. B., Sagi, E., Morbiwala, T. A., Tan, C.-T., & Svirsky, M. A. (2013). Feasibility
817 of Real-Time Selection of Frequency Tables in an Acoustic Simulation of a Cochlear
818 Implant. *Ear and Hearing*, 34(6), 763–772. doi: 10.1097/AUD.0b013e3182967534
- 819 Fox, J., & Weisberg, S. (2011). *An R Companion to Applied Regression* (Second). Retrieved
820 from <http://socserv.socsci.mcmaster.ca/jfox/Books/Companion>
- 821 Friesen, L. M., Shannon, R. V., Bařkent, D., & Wang, X. (2001). Speech recognition in noise
822 as a function of the number of spectral channels: Comparison of acoustic hearing and
823 cochlear implants. *The Journal of the Acoustical Society of America*, 110(2), 1150. doi:
824 10.1121/1.1381538
- 825 Frijns, > Johan HM, Kalkman, R. K., Vanpoucke, F. J., Bongers, J. S., & Briaire, J. J. (2009).
826 Simultaneous and non-simultaneous dual electrode stimulation in cochlear implants:
827 Evidence for two neural response modalities. *Acta Oto-Laryngologica*, 129(4), 433–
828 439. doi: 10.1080/00016480802610218

- 829 Fu, Q.-J., & Nogaki, G. (2005). Noise Susceptibility of Cochlear Implant Users: The Role of
830 Spectral Resolution and Smearing. *Journal of the Association for Research in*
831 *Otolaryngology*, 6(1), 19–27. doi: 10.1007/s10162-004-5024-3
- 832 Fu, Q.-J., & Shannon, R. V. (1999). Effects of Electrode Configuration and Frequency
833 Allocation on Vowel Recognition with the Nucleus-22 Cochlear Implant. *Ear and*
834 *Hearing*, 20(4), 332. doi: 10.1097/00003446-199908000-00006
- 835 Fu, Q.-J., & Shannon, R. V. (2002). Frequency mapping in cochlear implants. *Ear and Hearing*,
836 23(4), 339–348.
- 837 Fu, Q.-J., Shannon, R. V., & Wang, X. (1998). Effects of noise and spectral resolution on vowel
838 and consonant recognition: Acoustic and electric hearing. *The Journal of the Acoustical*
839 *Society of America*, 104(6), 3586–3596.
- 840 Gaudrain, E., & Başkent, D. (2015). Factors limiting vocal-tract length discrimination in
841 cochlear implant simulations. *The Journal of the Acoustical Society of America*, 137(3),
842 1298–1308. doi: 10.1121/1.4908235
- 843 Gaudrain, E., & Başkent, D. (2018). Discrimination of Voice Pitch and Vocal-Tract Length in
844 Cochlear Implant Users. *Ear and Hearing*, 39, 226–237. doi:
845 10.1097/AUD.0000000000000480
- 846 Grasmeder, M. L., Verschuur, C. A., & Batty, V. B. (2014). Optimizing frequency-to-electrode
847 allocation for individual cochlear implant users. *The Journal of the Acoustical Society*
848 *of America*, 136(6), 3313–3324. doi: 10.1121/1.4900831
- 849 Green, D., & Swets, J. (1966). *Signal detection theory and psychophysics*. New York: Wiley.
- 850 Hahlbrock, D. K.-H. (1953). Über Sprachaudiometrie und neue Wörtertete. *Archiv für Ohren-*
851 *, Nasen- und Kehlkopfheilkunde*, 162(5), 394–431. doi: 10.1007/BF02105664

- 852 Hanekom, J. J., & Shannon, R. V. (1998). Gap detection as a measure of electrode interaction
853 in cochlear implants. *The Journal of the Acoustical Society of America*, *104*(4), 2372–
854 2384. doi: 10.1121/1.423772
- 855 Henry, B. A., & Turner, C. W. (2003). The resolution of complex spectral patterns by cochlear
856 implant and normal-hearing listeners. *The Journal of the Acoustical Society of America*,
857 *113*(5), 2861–2873. doi: 10.1121/1.1561900
- 858 Hochmair-Desoyer, I., Schulz, E., Moser, L., & Schmidt, M. (1997). The HSM sentence test as
859 a tool for evaluating the speech understanding in noise of cochlear implant users. *The*
860 *American Journal of Otology*, *18*(6 Suppl), S83.
- 861 Ives, D. T., Smith, D. R. R., & Patterson, R. D. (2005). Discrimination of speaker size from
862 syllable phrases. *The Journal of the Acoustical Society of America*, *118*(6), 3816–3822.
863 doi: 10.1121/1.2118427
- 864 Kawahara, H., & Irino, T. (2005). Underlying Principles of a High-quality Speech Manipulation
865 System STRAIGHT and Its Application to Speech Segregation. In P. Divenyi (Ed.),
866 *Speech Separation by Humans and Machines* (pp. 167–180). Boston, MA: Springer.
- 867 Langner, F., Saoji, A. A., Büchner, A., & Nogueira, W. (2017). Adding simultaneous
868 stimulating channels to reduce power consumption in cochlear implants. *Hearing*
869 *Research*, *345*, 96–107.
- 870 Leigh, J. R., Henshall, K. R., & McKay, C. M. (2004). Optimizing Frequency-to-Electrode
871 Allocation in Cochlear Implants. *Journal of the American Academy of Audiology*, *15*(8),
872 574–584. doi: 10.3766/jaaa.15.8.5
- 873 Levitt, H. (1971). Transformed Up-Down Methods in Psychoacoustics. *The Journal of the*
874 *Acoustical Society of America*, *49*(2B), 467–477. doi: 10.1121/1.1912375

- 875 Licklider, J. (1954). “Periodicity” pitch and “place” pitch. *The Journal of the Acoustical Society*
876 *of America*, 26(5), 945–945. doi: 10.1121/1.1928005
- 877 Lieberman, P., & Blumstein, S. E. (1988). Source-filter theory of speech production. In *Speech*
878 *Physiology, Speech Perception, and Acoustic Phonetics* (pp. 34–50). Cambridge
879 University Press.
- 880 Lo, S., & Andrews, S. (2015). To transform or not to transform: Using generalized linear mixed
881 models to analyse reaction time data. *Frontiers in Psychology*, 6:1171, 1–16. doi:
882 10.3389/fpsyg.2015.01171
- 883 McKay, C. M., & Henshall, K. R. (2002). Frequency-to-electrode allocation and speech
884 perception with cochlear implants. *The Journal of the Acoustical Society of America*,
885 111(2), 1036. doi: 10.1121/1.1436073
- 886 McKay, C. M., & McDermott, H. J. (1999). The perceptual effects of current pulse duration in
887 electrical stimulation of the auditory nerve. *The Journal of the Acoustical Society of*
888 *America*, 106(2), 998–1009. doi: 10.1121/1.428052
- 889 Molenaar, D., Tuerlinckx, F., van der Maas, H. L., & others. (2015). Fitting diffusion item
890 response theory models for responses and response times using the R package diffIRT.
891 *Journal of Statistical Software*, 66(4), 1–34.
- 892 Müller, J. (1848). *The Physiology of the Senses, Voice, and Muscular Motion, with the Mental*
893 *Faculties...* London, UK: Taylor, Walton & Maberly.
- 894 Nelson, P. B., & Jin, S.-H. (2004). Factors affecting speech understanding in gated interference:
895 Cochlear implant users and normal-hearing listeners. *The Journal of the Acoustical*
896 *Society of America*, 115(5), 2286–2294.

- 897 Nogueira, W., Litvak, L. M., Edler, B., Ostermann, J., & Büchner, A. (2009). Signal Processing
898 Strategies for Cochlear Implants Using Current Steering. *EURASIP Journal on*
899 *Advances in Signal Processing*, 2009, 1–21. doi: 10.1155/2009/531213
- 900 Nogueira, W., Schurzig, D., Büchner, A., Penninger, R. T., & Würfel, W. (2016). Validation of
901 a cochlear implant patient-specific model of the voltage distribution in a clinical setting.
902 *Frontiers in Bioengineering and Biotechnology*, 4, 84.
- 903 Omran, S. A., Lai, W., & Dillier, N. (2011). Pitch Ranking, Melody Contour and Instrument
904 Recognition Tests Using Two Semitone Frequency Maps for Nucleus Cochlear
905 Implants. *EURASIP Journal on Audio, Speech, and Music Processing*, 2010(1), 948565.
906 doi: 10.1155/2010/948565
- 907 Oxenham, A. J. (2008). Pitch perception and auditory stream segregation: Implications for
908 hearing loss and cochlear implants. *Trends in Amplification*, 12(4), 316–331. doi:
909 10.1177/1084713808325881
- 910 Pals, C., Sarampalis, A., Beynon, A., Stainsby, T., & Başkent, D. (2016). Effect of spectral
911 resolution on speech intelligibility, comprehension, and listening effort in cochlear-
912 implant users. In *Listening Effort: The hidden costs and benefits of cochlear implants*
913 (pp. 84–107). Retrieved from
914 https://www.rug.nl/research/portal/files/35879879/Complete_thesis.pdf
- 915 Peterson, G. E., & Barney, H. L. (1952). Control methods used in a study of the vowels. *The*
916 *Journal of the Acoustical Society of America*, 24(2), 175–184. doi: 10.1121/1.1906875
- 917 Qin, M. K., & Oxenham, A. J. (2003). Effects of simulated cochlear-implant processing on
918 speech reception in fluctuating maskers. *The Journal of the Acoustical Society of*
919 *America*, 114(1), 446–454. doi: 10.1121/1.1579009

920 R Core Team. (2017). *R: A Language and Environment for Statistical Computing*. Retrieved
921 from <https://www.R-project.org/>

922 Ratcliff, R. (1978). A theory of memory retrieval. *Psychological Review*, *85*(2), 59–108. doi:
923 10.1037/0033-295X.85.2.59

924 Ratcliff, R., Smith, P. L., Brown, S. D., & McKoon, G. (2016). Diffusion decision model:
925 Current issues and history. *Trends in Cognitive Sciences*, *20*(4), 260–281. doi:
926 10.1016/j.tics.2016.01.007

927 Schaffrath Rosario, A., Schienkiewitz, A., & Neuhauser, H. (2011). German height references
928 for children aged 0 to under 18 years compared to WHO and CDC growth charts. *Annals*
929 *of Human Biology*, *38*(2), 121–130.

930 Shannon, R. V. (1983). Multichannel electrical stimulation of the auditory nerve in man. II.
931 Channel interaction. *Hearing Research*, *12*(1), 1–16. doi: 10.1016/0378-
932 5955(83)90115-6

933 Shannon, R. V. (1985). Threshold and loudness functions for pulsatile stimulation of cochlear
934 implants. *Hearing Research*, *18*(2), 135–143. doi: 10.1016/0378-5955(85)90005-X

935 Shannon, R. V. (1989). A model of threshold for pulsatile electrical stimulation of cochlear
936 implants. *Hearing Research*, *40*(3), 197–204. doi: 10.1016/0378-5955(89)90160-3

937 Smith, D. R. R., & Patterson, R. D. (2005). The interaction of glottal-pulse rate and vocal-tract
938 length in judgements of speaker size, sex, and age. *The Journal of the Acoustical Society*
939 *of America*, *118*(5), 3177–3186. doi: 10.1121/1.2047107

940 Smith, D. R. R., Patterson, R. D., Turner, R., Kawahara, H., & Irino, T. (2005). The processing
941 and perception of size information in speech sounds. *The Journal of the Acoustical*
942 *Society of America*, *117*(1), 305–318. doi: 10.1121/1.1828637

- 943 Stevens, K. N., & House, A. S. (1955). Development of a quantitative description of vowel
944 articulation. *The Journal of the Acoustical Society of America*, 27(3), 484–493. doi:
945 10.1121/1.1907943
- 946 Townshend, B., & White, R. L. (1987). Reduction of electrical interaction in auditory
947 prostheses. *IEEE Transactions on Biomedical Engineering, BME-34*(11), 891–897. doi:
948 10.1109/TBME.1987.326102
- 949 Wagenmakers, E.-J., Van Der Maas, H. L., & Grasman, R. P. (2007). An EZ-diffusion model
950 for response time and accuracy. *Psychonomic Bulletin & Review*, 14(1), 3–22. doi:
951 10.3758/BF03194023
- 952 Winn, M. B., Won, J. H., & Moon, I. J. (2016). Assessment of Spectral and Temporal
953 Resolution in Cochlear Implant Users Using Psychoacoustic Discrimination and Speech
954 Cue Categorization. *Ear and Hearing*, 37(6), e377–e390. doi:
955 10.1097/AUD.0000000000000328
- 956