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Sensory-motor relationships in speech production in post-lingually deaf cochlear-implanted adults and normal-hearing seniors: evidence from phonetic convergence and speech imitation

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Abstract:

Speech communication can be viewed as an interactive process involving a functional coupling between sensory and motor systems. One striking example comes from phonetic convergence, when speakers automatically tend to mimic their interlocutor's speech during communicative interaction. The goal of this study was to investigate sensory-motor linkage in speech production in postlingually deaf cochlear implanted participants and normal hearing elderly adults through phonetic convergence and imitation. To this aim, two vowel production tasks, with or without instruction to imitate an acoustic vowel, were proposed to three groups of young adults with normal hearing, elderly adults with normal hearing and post-lingually deaf cochlear-implanted patients. Measure of the deviation of each participant's f_0 from their own mean f_0 was measured to evaluate the ability to converge to each acoustic target.

Results showed that cochlear-implanted participants have the ability to converge to an acoustic target, both intentionally and unintentionally, albeit with a lower degree than young and elderly participants with normal hearing. By providing evidence for phonetic convergence and speech imitation, these results suggest that, as in young adults, perceptuo-motor relationships are efficient in elderly adults with normal hearing and that cochlear-implanted adults recovered significant perceptuo-motor abilities following cochlear implantation.

Key-words: Phonetic convergence, imitation, cochlear implant, elderly, sensory-motor interactions, speech production

1 **1. Introduction**

2 **1.1.Sensory-motor interactions in speech perception and speech production**

3 In the speech communication domain, an old and fundamental debate concerns the nature of processes
4 and representations involved in speech perception and production. Concerning speech perception,
5 auditory theories assume that speech perceptual processing and categorization are based on acoustic
6 features and auditory representations (Stevens and Blumstein 1978, 1979; Lindblom et al. 1988, 1990).
7 Conversely, the motor theory of speech perception (Liberman et al., 1985) or the direct realist theory
8 (Fowler, 2005) respectively claim that speech perception involves the recovery of the speaker's motor
9 intentions or articulatory gestures. More recently, various perceptuo-motor theories introduced
10 syntheses of arguments by tenants of both auditory and motor theories, and proposed that implicit
11 motor knowledge and motor representations are used in relationship with auditory representations and
12 processes to elaborate phonetic decisions (Skipper et al., 2007; Schwartz et al., 2012). These theories
13 capitalize on the increasing amount of evidence for the role of motor representations and processes in
14 speech perception (see a recent review in Skipper et al., 2017).

15 Concerning speech production, various theories have also been introduced to characterize the
16 speaker's goals. Motor or articulatory theories, like Task dynamics (Saltzman, 1986) and the
17 associated Articulatory Phonology (Browman & Goldstein, 1992), consider that speech targets are
18 defined in the articulatory space. On the contrary, auditory theories like Stevens' Quantal Theory
19 (Stevens 1972, 1988) and Perkell's speech production control model (Perkell et al. 1995, 2000),
20 suggest that targets are specified in auditory terms. Finally, sensory-motor models claim that speech
21 production control is multimodal and combines auditory and somatosensory information (see Perrier,
22 2005; and the DIVA model, Guenther et al. 1998, Guenther & Vladusich, 2012). A number of data
23 about the effect of auditory (e.g. Lametti et al., 2014; Shiller & Rochin, 2014) or somatosensory
24 (Tremblay et al., 2003) perturbations applied to speech production in adults or children are in
25 agreement with this sensory-motor framework.

26 From a number of these theories, sensory-motor relationships seem to play an important role in
27 both speech perception and speech production in normal conditions. The present study deals with
28 subjects for which some degradation of the sensory-motor link could be expected, because of sensory
29 deficits. The first and primary situation is the case of post-lingually deaf subjects equipped with
30 cochlear implants. Indeed, post-lingually deaf subjects are expected to have acquired efficient sensory-
31 motor relationships before deafness. Their ability to achieve intelligible speech production is
32 interpreted as evidence that they have maintained a stable and rather accurate internal model of these
33 sensory-motor relationships all along their deafness life (Perkell et al., 2000). Cochlear implantation
34 then results in providing them with a new kind of auditory input, quite different from the one they had
35 acquired before deafness considering the very special nature of cochlear-implant coding of acoustic
36 information. The question is to know how the internal relationships between these “new” auditory
37 inputs, the “old” ones acquired at the first stages of development, and the motor representations are
38 established and organized, and how efficient they are.

39 A number of data on speech production after cochlear implantation display an increase in acoustic
40 dispersion of vowels after a few months of implantation (e.g. Langereis et al., 1998; Lane et al., 2005;
41 Ménard et al., 2007), suggesting that the internal model has indeed benefited from the new auditory
42 input provided by cochlear implantation. Interestingly however, some studies explored the response to
43 articulatory perturbation using a bite-block task (Lane et al., 2005), a robotic device displacing the jaw
44 during speech (Nasir & Ostry, 2008) or a lip-tube task (Turgeon, Prémont, Trudeau-Fisette, & Ménard,
45 2015), with or without auditory feedback. Results showed that post-lingual cochlear-implanted
46 participants (CI) are able to adapt their articulatory trajectory when it is perturbed in order to reach
47 their auditory goals and make their production intelligible, even when the implant is turned off. Such
48 compensatory strategies show that perceptuo-motor abilities acquired during speech acquisition in CI
49 subjects are still at work after deafness, though the addition of auditory information provided by the
50 cochlear-implant does result in enhanced precision and efficiency of the sensory-motor internal model.
51 Finally, a PET-scanning study on visual speech perception in post-lingually deaf CI patients (Rouger
52 et al., 2012) showed that after a short adaptation period with the implant, there was a decrease of the

53 initially abnormal activity in the superior temporal sulcus, a cross-modal brain area, accompanied by a
54 progressive reactivation of frontal premotor speech areas. This suggests that sensorimotor
55 neuroplasticity after cochlear implantation provides a progressive reactivation of the audio-visuo-
56 motor linkage in CI subjects.

57 The second situation considered in the present study is the case of elderly subjects. They are of
58 interest for us for two reasons. The first one is the interest of assessing the consequences of the
59 potential decline of cognitive and language abilities in relation with decline in sensory and motor
60 accuracy on the efficiency of sensory-motor relationships. The second reason is that a number of the
61 cochlear-implanted post-lingually deaf participants are rather old, and we considered important to
62 include senior subjects with no severe auditory deficit as a control population. As a matter of fact, very
63 few studies investigated perceptuo-motor relationships in elderly population. One of them shows that
64 elderly people adapt their production in case of degraded auditory feedback (Liu et al., 2010, 2011).
65 Sensorimotor neuroplasticity was also observed in elderly people, linked with age-dependent
66 intelligibility effects mainly found in auditory and motor cortical areas (Tremblay, Dick, & Small,
67 2013; Bilodeau-Mercure, Ouellet, & Tremblay, 2015). Taken together, these behavioral and neuro-
68 imaging studies suggest that sensory-motor relationships are well preserved in aging.

69 **1.2. Phonetic convergence and imitation, a paradigm for studying sensory-motor** 70 **relationships in speech**

71 Imitation is a quite widespread phenomenon in speech communication and can be viewed as a key
72 mechanism in the acquisition of human language. In interactive situations, adult speakers tend to
73 continuously adapt their productions to those of their interlocutor, in order to facilitate communicative
74 exchanges. These adaptive changes in speech production can be voluntary, that is when the speaker
75 consciously imitates his interlocutor, but also unintentional. Indeed, unintentional imitation, or
76 phonetic convergence, that is the tendency to automatically imitate a number of acoustic-phonetic
77 characteristics in the productions of an interacting speaker, has been displayed in various studies (see a
78 recent collection of papers on this topic in Nguyen et al., 2013, and for recent reviews see Babel, 2009;
79 Aubanel, 2011; Lelong, 2012). In these studies, convergence effects have been observed both in

80 paralinguistic features, such as gestures, and in speech acoustic parameters, such as intensity,
81 fundamental frequency f_0 or formants. These phonetic convergence effects may be related to the social
82 component of communication, assuming that they would contribute to setting a common ground
83 between speakers (Giles, Coupland, & Coupland, 1991) and that they could be associated to the
84 human desire of affiliation to a social group.

85 Interestingly however, while most reports on phonetic convergence are based on conversational
86 exchanges in natural conditions, a few studies showed that phonetic convergence can also be observed
87 using laboratory settings involving non-interactive situations of communication (Goldinger & Azuma,
88 2004; Gentilucci & Cattaneo, 2005; Delvaux & Soquet, 2007; Garnier, Lamalle, & Sato, 2013; Sato et
89 al., 2013). For example, Delvaux & Soquet (2007) obtained phonetic convergence effects during the
90 production of auditorily presented words without interaction, and they also reported offline adaptation
91 to the auditory targets in post-tests following stimulus exposure. These studies hence suggest that
92 phonetic convergence is not only a matter of social attunement, but could also involve a more basic
93 stage of continuous automatic adaptation of the speech production system to the external speech
94 sounds environment (for a recent review, see Sato et al., 2013).

95 Such an automatic adaptation mechanism requires the existence of a sensory-motor coupling
96 process in which variations in the external environment provide sensory targets that drive motor
97 control procedures to adapt and produce stimuli closer to these external targets. More in detail, the
98 speaker would program motor commands to achieve an articulatory and ultimately an auditory (or
99 more generally sensory) goal according to the linguistic message to be conveyed to the listener. Then,
100 in the course of speech production, the speaker would compare sensory feedback to the initial sensory
101 objective. Variations in the external environment would shift the sensory targets and accordingly result
102 in modifications of motor commands to converge towards speech sounds in the environment. Hence,
103 the convergence/imitation paradigm is a natural tool to study sensory-motor coupling in speech
104 communication.

105 Phonetic convergence and imitation in laboratory settings can involve various kinds of acoustic
106 features, though fundamental frequency effects seem to be larger and easier to obtain than variations in

107 e.g. formant values (Sato et al., 2013). The present study therefore focus on convergence and imitation
108 on f_0 variations.

109 **1.3.f0 perception and motor control in cochlear-implanted adults and normal-hearing** 110 **seniors**

111 Past studies on pitch control in speech production by CI subjects reported higher f_0 values for CI
112 adults than for adults with normal hearing and, more importantly, larger variations in f_0 for CI than for
113 adults with normal hearing (e.g. Lane & Webster, 1991). Langereis (1998) and Kishon-Rabin et al.
114 (1999) also reported that while pitch production is generally altered in CI patients soon after
115 implantation, almost normal f_0 values were observed one year post-implantation for two participants in
116 Kishon-Rabin et al. (1999) study. Notice that technological evolutions led to important progress in the
117 coding of pitch in cochlear implants since these studies.

118 Concerning speech perception, several factors appear to influence performance in CI patients. In
119 Blamey et al. (2012), 2251 CI patients participated to a battery of auditory tests, where they had to
120 recognize phonemes, words and sentences. The experimenters reported that both duration of implant
121 experience, age at onset of severe to profound hearing loss, age at cochlear implantation and duration
122 of deafness influence speech perception to a certain extent – though inter-subject variability was quite
123 large in this kind of study. Regarding f_0 , for cochlear-implanted patients, pitch is difficult to estimate
124 because of different reasons. First, as the implant is composed of 12 to 22 electrodes, the merging of
125 frequencies in a given electrode likely impacts frequency discrimination by patients. Furthermore,
126 because of their proximity, electrodes can stimulate nerve fibers, which do not correspond to the
127 intended frequency, which leads to an imperfect tonotopy restitution.

128 Regarding elderly people, it is well known that auditory capacities decline with aging. More
129 specifically, even with close-to-normal auditory thresholds, elderly people with normal hearing
130 present difficulties in adverse listening conditions, e.g. in a noisy environment (Gelfand, Piper, &
131 Silman, 1985; Ohde & Abou-Khalil, 2001; Fullgrabe, 2013). The role of cognitive functions in this
132 decline of speech perception is still under debate (Cienkovski & Camey, 2002; Cienkovski & Vasil-
133 Dilaj, 2010; Moore & Fullgrabe, 2013; see a review in Fullgrabe & Rosen, 2016). On the motor side,
134 elderly people also show deficits in orofacial movements, which might impact speech production.

135 Indeed, a majority of studies demonstrate a degradation of speech production in elderly people, with
136 more variable and less stable speech utterances than observed in younger adults. An alteration of voice
137 control is also observed in elderly people, notably with higher pitch variability and less stable pitch
138 production at the level of individual subjects (Morgan & Rastatter, 1986; Russell, Penny, &
139 Pemberton, 1995; Lortie, Thibeault, Guitton, & Tremblay, 2015).

140 **1.4. Goal of the study**

141 In the present study, voluntary and unintentional imitative changes were tested during speech
142 production in both post-lingually deaf or hearing impaired adults equipped with a cochlear implant and
143 in seniors with normal hearing. Our goal was to explore in these populations the underlying perceptuo-
144 motor mechanisms at work in phonetic convergence and speech imitation. To this aim, we capitalized
145 on two recent studies by Sato et al. (2013) and Garnier et al. (2013) displaying both unintentional and
146 voluntary imitative changes on fundamental frequency of auditorily presented vowel targets during
147 speech production in a non-interactive situation of communication. In these studies, participants were
148 asked to produce different vowels according to acoustic targets with their pitch varying around the
149 averaged pitch of their own voice, with or without instruction to imitate the target. Results showed that
150 participants strongly converged to the vowel target not only in the imitative task, but also, at a lower
151 degree, in the production task even if no instruction to imitate the vowel target was given.

152 To our knowledge, convergence and imitation abilities have never been studied either in CI
153 subjects or in elderly people with normal hearing. We here report online imitative changes on the
154 fundamental frequency in relation to acoustic vowel targets in a non-interactive situation of
155 communication during both unintentional and voluntary imitative production tasks in the two studied
156 populations. Our goal was to determine to which extent CI and elderly participants display
157 convergence and imitation abilities, and to compare these abilities with those observed in young adults
158 with normal hearing (NHY), with the larger aim to evaluate sensory-motor linkage during speech
159 production in CI and elderly population. Three populations have been contrasted: post-lingually deaf
160 or hearing-impaired cochlear-implanted adults (generally not very young), senior adults with no
161 specific auditory deficit apart from aging, and normal-hearing young adults as a control. The same

162 paradigm as the one developed by Garnier et al. (2013) and Sato et al. (2013) was exploited in this
163 study.

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167 **2. Methods**168 **2.1. Participants**

169 Three groups of participants performed the experiment. The first group consisted of fifteen young
170 participants with normal hearing (NHY) (10 females and 5 males, mean age: 30 years old, range: 20-
171 40) who reported no history of speaking, hearing or motor disorders. The second group consisted of
172 ten elderly participants with normal hearing (NHE) (4 females and 6 males, mean age: 69 years old,
173 range: 63-78). The third group consisted of ten post-lingually deaf cochlear-implanted (CI)
174 participants (7 males and 3 females, mean age: 58.9 years old, range: 27-76). As indicated in Table 1,
175 the CI group was heterogeneous in several aspects: age at onset of deafness varied from 7 to 65 years,
176 duration of deafness varied from 1 month to 58 years and duration of cochlear implant experience
177 varied from 1 month to 9 years. In addition, seven of the ten participants wore classical hearing aid in
178 the non-implanted ear, and one participant was bilaterally implanted. The experiment was performed
179 in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

180

Insert Table 1 about here

181

182 **2.2. Stimuli**

183 A vowel database was created from /e/, /oe/, /o/ French vowels produced by one male and one female
184 speaker. For each vowel, one clearly articulated occurrence was selected and digitized at 44.1 kHz.
185 From these stimuli, f_0 was artificially shifted by steps of ± 5 Hz (from 80Hz to 180Hz for the male
186 vowels, and from 150 to 350Hz for the female vowels) using the PSOLA module integrated in the
187 Praat software (Boersma and Weenink, 2013). These stimuli allowed us to present to each participant
188 nine distinct stimuli per vowel ranging from -20% and +20% from the mean participant's f_0 by steps of
189 5% (-20%, -15%, -10%, -5%, 0%, +5%, +10%, +15%, +20%).

190 **2.3. Experimental procedure**

191 The experiment was carried out in a sound-proof room. Participants sat in front of a computer monitor
192 at a distance of approximately 50 cm. The acoustic stimuli were presented at a comfortable sound level

193 through a loudspeaker, with the same sound level set for all participants. The Presentation software
194 (Neurobehavioral Systems, Albany, CA) was used to control the stimulus presentation during all
195 experiments. All participants' productions were recorded for off-line analyses.

196 The experiment consisted of three vowel production tasks. First, participants had to individually
197 produce /e/, /æ/ and /o/ vowels, according to a visual orthographic target. This allowed the
198 experimenter to measure the participant's f_0 . In the subsequent task (which will be referred by
199 "convergence task"), participants were asked to produce the three vowels according to an acoustic
200 target. Importantly, no instruction to "repeat" or to "imitate" the acoustic targets was given to the
201 participants. Finally, the third task (which will be referred by "imitative task") was the same as the
202 second task except that participants were explicitly asked to imitate the acoustic targets. The only
203 indication given to participants was to imitate the voice characteristics of the perceived speaker.
204 Importantly, we hence kept a fixed order of the "convergence" and "imitative" tasks so as to avoid
205 cases in which prior explicit imitation instructions could modify further convergence effects and add
206 conscious imitation strategies to automatic convergence processes.

207 Acoustic targets in the "convergence" and "imitative" tasks for each participant consisted in the 27
208 stimuli selected from the vowel database (9 per vowel category), repeated three times each so as to
209 obtain 81 trials altogether. Each participant was presented with one model talker of the same sex, with
210 the 9 quantified f_0 frequencies varying from -20% to +20% by steps of 5% around his/her own pitch,
211 as measured in the first task.

212 At the end of the experiment, participants were asked to perform a frequency discrimination test to
213 estimate their pitch just noticeable difference (JND), based on an experimental paradigm proposed by
214 Vinay & Moore (2010). Two groups of four sounds were presented to participants in a random order,
215 composed either of identical sounds (AAAA) or of two sounds A and B differing in pitch (ABAB),
216 and participants had to determine in which group sounds were different among each other. We used
217 synthesized stimuli, obtained by addition of harmonics of a given f_0 value, with 0 phase and amplitude
218 based on the spectrum of a vowel /e/ produced by either a male or a female, depending of the
219 participant's gender. For sound A, the f_0 value was set at the participant's mean production value. For
220 sound B, the selected f_0 value was systematically higher than f_0 for sound A, beginning with a 5%

221 deviation further varying along the test. Moreover, small random intensity variations were applied to
222 the two groups of sounds from one trial to the other, in order to force the participant to focus on pitch
223 rather than timbre or intensity perception (Vinay & Moore, 2010). Variations of the f_0 values for sound
224 B were driven by an adaptive two-alternative forced choice procedure: after two consecutive correct
225 answers, the frequency difference between sounds A and B decreased, whereas one mistake drove an
226 increase of this difference. The test result corresponded to the mean of the difference between f_0 values
227 for sound A and sound B for the last eight trials.

228 **2.4.Data analysis**

229 All acoustic analyses of participants' productions were performed using the Praat software (Boersma
230 & Weenink, 2013). In the second and third tasks which both involved an acoustic target (/e/, /æ/ or /o/)
231 that could possibly be misunderstood by the participant, we annotated the participant productions in
232 order to estimate the percentage of errors in production in relation to the target.

233 Analysis began by a semi-automatic segmentation procedure aiming at segmenting each individual
234 vowel produced by a given participant in a given task. Using intensity and duration criteria, the
235 algorithm automatically identified pauses between each vowel and segmented individual productions
236 accordingly. Segmentation was hand-corrected when appropriate, checking waveform and
237 spectrogram. Only correctly produced vowels (that is, checked by the experimenter as corresponding
238 to the phonemic target) were further analyzed. For each correctly produced vowel, f_0 was determined
239 within a time frame around ± 25 ms of the maximum intensity of the sound file.

240 **2.5.Statistical analysis**

241 For each subject and task, there were altogether 9 values of f_0 production per target f_0 value between -
242 20% and 20% (with 3 vowel types and 3 utterances per type). The mean of the 9 produced f_0 values
243 was computed, and linear regression between mean produced f_0 values and f_0 targets was computed for
244 each participant separately in the convergence and imitation tasks,. The slope and correlation
245 coefficients were then determined for each task and each participant. Individual t-tests were done on
246 these correlation coefficients to determine if they were significant.

247 For each group, one-tailed t-tests were then performed on individual slope and correlation
248 coefficients compared to zero in order to determine significant imitative changes in each task. To test

249 for possible differences in imitative changes from one task to the other, additional t-tests were
250 performed on slope and correlation coefficients between the two tasks. However, it is important to
251 remind that the order between the two tasks being not counterbalanced, any difference between them
252 can be interpreted both as a consequence of difference in tasks and order effect.

253 In addition, in order to test whether imitative changes in the convergence and imitation tasks may
254 correlate among speakers, a Pearson's correlation analysis was performed between slope coefficients.
255 Finally, Pearson's correlation analyses were performed between slope coefficients and JND values
256 within each group of participants and for each task, as well as between slope coefficients and age,
257 duration of deafness, age at implantation, age at the beginning of deafness and duration of implant
258 experience for CI participants in each task.

259 To compare the results of the three groups, a repeated-measures ANOVA was finally performed on
260 slope coefficients with the group (NHY vs. NHE vs. CI) as between-subject variable and the task
261 (convergence vs. imitation) as within-subject variable. Additionally, a one-factor ANOVA was
262 performed on JND values, with group as categorical factor. The sphericity assumption was tested
263 using a Mauchly test and, when necessary, Greenhouse-Geiser corrections were applied (Greenhouse
264 and Geiser, 1959).

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270 3. Results

271 3.1. Young participants with normal hearing (see Figure 1)

272 For NHY participants, imitative changes were observed in both tasks, though stronger during
273 voluntary imitation. Slope coefficients differed significantly from zero in both the convergence
274 ($t(14)=5.98$; $p<0.001$) and imitation ($t(14)=35.78$; $p<0.001$) tasks. In addition, slope coefficients were
275 higher in the imitation compared to the convergence tasks (on average: 0.87 vs. 0.45; $t(14)=6.02$;
276 $p<.001$). No significant correlation was observed between the slope coefficients in the convergence
277 and imitation tasks ($r^2=0.12$).

278 Similarly, correlation coefficients differed significantly from zero in both the convergence ($t(14)=8.3$;
279 $p<0.001$) and imitation ($t(14)=93.34$; $p<0.001$) tasks, and were higher in the imitation compared to the
280 convergence task (on average: 0.94 vs. 0.64; $t(14)=4.3$; $p<0.001$). Individual analyses showed that
281 fourteen of the sixteen participants converged to the target in the convergence task (r^2 from 0.05 to
282 0.99), and in the imitative task all of the participants converged to the target (r^2 from 0.91 to 1).

283 JND values for NHY participants were at 1.06 Hz on average (range: 0.14 to 3.88 Hz), with no
284 significant correlation between the slope coefficients in the convergence or the imitation tasks and
285 JND values (convergence: $r^2=0.00$ $p=.82$, imitation: $r^2=0.00$ $p=.9$).

286 Insert Figure 1 about here

287

288 3.2. Elderly participants with normal hearing (see Figure 2)

289 For NHE participants, imitative changes were observed in both tasks, though stronger in voluntary
290 imitation. Slope coefficients differed significantly from zero in both the convergence ($t(9)=3.52$;
291 $p<0.01$) and imitation ($t(9)=8.5$; $p<0.001$) tasks. In addition, slope coefficients were higher in the
292 imitation compared to the convergence task (on average: 0.75 vs. 0.33; $t(9)=4.97$; $p<.001$). There was
293 no significant correlation between convergence and imitation tasks ($r^2=0.59$).

294 Similarly, correlation coefficients differed significantly from zero in both the convergence ($t(9)=5.96$;
295 $p<0.001$) and imitation ($t(9)=11.78$; $p<0.001$) tasks, and were higher in the imitation compared to the

296 convergence tasks (on average: 0.84 vs. 0.54; $t(9)=4.12$; $p<0.001$). Individual analyses showed that
297 eight of the ten participants converged to the target in the convergence task (r^2 from 0.35 to 0.99), and
298 in the imitative task all of the participants except one converged to the target (r^2 from 0.28 to 0.99).

299 JND values for NHE participants were at 0.95 Hz on average (range: 0.43 to 1.8 Hz) with no
300 correlation with either the convergence or the imitation slopes (convergence: $r^2=0.03$ $p=.63$ imitation:
301 $r^2=0.00$ $p=.79$).

302 Insert Figure 2 about here

303

304 3.3. Cochlear-implanted participants (see Figure 3)

305 As for NHY and NHE participants, imitative changes were also observed in both tasks for CI
306 participants. Slope coefficients differed significantly from zero in both the convergence ($t(9)=3.24$;
307 $p<0.02$) and imitation ($t(9)=4.84$); $p<0.001$) tasks. In addition, slope coefficients were higher in the
308 imitation compared to the convergence tasks (on average: 0.39 vs. 0.14; $t(9)=3.53$; $p<0.001$). As for
309 NH participants, there was no significant correlation between convergence and imitation tasks
310 ($r^2=0.28$).

311 Similarly, correlation coefficients differed significantly from zero in both the convergence ($t(9)=4.08$;
312 $p<0.01$) and imitation ($t(9)=5.53$; $p<0.001$) tasks, and were higher in the imitation compared to the
313 convergence tasks (on average: 0.49 vs. 0.24; $t(9)=2.95$; $p<0.02$).

314 JND values for CI participants were at 14.06 Hz on average (range: 1.71 to 45.35 Hz). There was also
315 no correlation between the convergence or imitation tasks and the others factors, that are JND values,
316 age, deafness duration, age at implantation, age at the beginning of deafness and duration of implant
317 experiment (all $r^2<0.3$).

318 While young and elderly participants with normal hearing made no errors in both tasks, cochlear-
319 implanted participants made a number of errors in both tasks, with similar error percentage in the
320 convergence (15%) and imitation tasks (13%). In order to verify if these errors influence convergence
321 effects, correlations between production and target were measured in both tasks on error trials only, for
322 participants presenting at least 15% of errors (four participants in each task). The correlation values
323 are displayed in Table 2. For those participants, correlations between production and target for error

324 trials appear similar to those obtained for correct trials in both convergence and imitation tasks. As a
325 matter of fact, the correlation values for correct trials and for error trials (when they are sufficient to do
326 computations) are highly correlated among the 8 cases where both can be computed ($r^2=0,71$,
327 $t(6)=3,81$, $p<0,005$).

328 To relate convergence effects with etiology variability and JND values, we report determination
329 coefficients in both tasks for each participant (see Table 2). In the convergence task, we obtained
330 significant correlation between target and production for five participants, with determination
331 coefficients from 0.05 and 0.75. In the imitative task, correlation is significant for seven participants,
332 with determination coefficients from 0.09 and 0.94. As shown in Table 2, the participants with no
333 significant convergence in one or the other tasks do not display obvious similarity in etiology in e.g.
334 age at deafness onset or deafness duration. Importantly, clear convergence in both tasks is obtained for
335 some subjects after a quite reduced duration of implantation: see the cases of subjects CI1, CI2, CI5 or
336 CI9 with significant convergence or imitation on f_0 after 1 to 5 months of implantation.

337 Concerning JND values, the participants with no significant convergence in one or the other tasks
338 do not present the worst JND values, and the participant with the highest JND value obtains significant
339 convergence effect in both tasks. More strikingly, the corresponding JND value for this subject, at 45
340 Hz, is actually larger than the largest variation in F0 applied to the stimuli in both convergence tasks.
341 As a matter of fact, F0 for this subject equals 125 Hz, and the maximal variation of F0 at 20% results
342 in a 25 Hz modification. Altogether, these facts converge to suggest that the task used for JND
343 estimation, well adapted for normal-hearing subjects (Vinay & Moore, 2010), is probably too complex
344 for cochlear-implanted subjects.

345 Insert Table 2 about here

346

347 Insert Figure 3 about here

348

349 **3.4. Comparison between groups (see Figure 4)**

350 The main effect of group was significant ($F_{(2,32)}=31.3$; $p<.001$) with lower mean slope coefficient for
351 CI participants than for NHY and NHE participants (CI: 0.26 ; NHY: 0.65 ; NHE: 0.55). No difference
352 was obtained between NHY and NHE groups. The main effect of task was also significant
353 ($F_{(1,32)}=67.29$; $p<.001$), with lower slope coefficients for the convergence task than for the imitation
354 task (convergence: 0.33 ; imitation: 0.69). No significant interaction was found between the group and
355 the task.

356 For the JND test, the effect of group was significant ($F_{(2,32)}=11.03$; $p<.001$), with larger values for
357 CI participants than for NHY and NHE participants (CI: 14.06; NHY: 1.06; NHE: 0.95) without
358 significant difference between NHY and NHE participants. This shows that CI participants stay
359 largely impaired in f_0 discrimination.

360 Insert Figure 4 about here

361

362

363 **4. Discussion**

364 The goal of this study was to investigate sensory-motor linkage in speech production on post-
365 linguually deaf cochlear-implanted patients, in comparison with young and elderly adults with normal
366 hearing, through the abilities of f_0 convergence and imitation. To this aim, we used a paradigm of
367 intentional and non-intentional imitation of vowels with modified fundamental frequency.

368 **4.1. Young adults**

369 We firstly replicated the previous findings by Sato et al. (2013) and Garnier et al. (2013) for young
370 adults with normal hearing. Imitative changes towards the acoustic target were indeed observed in
371 both tasks, with stronger convergence in the task with direct instruction than in the convergence task.
372 It is likely that this is mainly due to the effect of the explicit instruction, though we cannot discard the
373 possibility that order intervened here, with a trend to increase convergence in the second task just
374 becomes it comes after the first one. As in the two previous studies, no correlation was found between
375 the two tasks, that is individual f_0 changes in the convergence task were not related to those observed
376 in the imitative task among subjects. This lack of correlation could be due to ceiling effects provided
377 by the very high degree of convergence in the imitative task and the very low variability of these
378 imitative changes for almost all participants. These results confirm that convergence can occur even in
379 a non-interactive situation of communication, in line with previous studies (Goldinger & Azuma,
380 2004; Gentilucci & Cattaneo, 2005; Delvaux & Soquet, 2007; Garnier et al. 2013; Sato et al. 2013).
381 Such non-interactive phonetic convergence effects likely rely on low-level sensory-motor mechanisms
382 described in the Introduction section, according to which participants would first analyze the target
383 stimulus to elaborate their motor and sensory goals, resulting in an adaptation of their production to
384 the acoustic target.

385 **4.2. Elderly population**

386 The results for elderly participants with normal hearing were similar to those of young adults. Indeed,
387 NHE imitated the auditory target in the imitative task and converged towards the acoustic target in a
388 probably subconscious way in the convergence task. In addition, as for young participants with normal

389 hearing, no correlation was observed between the two tasks. The observed convergence effects in both
390 voluntary and unintentional imitation in this elderly population, as high as in young subjects, suggests
391 that sensory-motor relationships during speech production are efficient in these participants, which is
392 in line with previous studies suggesting that sensory-motor relationships are still active and efficient in
393 seniors (Liu et al., 2010, 2011, Tremblay et al. 2013).

394 **4.3. Post-lingually deaf cochlear-implanted participants**

395 In spite of their strongly impaired ability to discriminate frequencies, as displayed by JND values 10 to
396 15 times larger than those of subjects with normal hearing, it is striking that CI participants were also
397 found to be able to imitate and to converge towards the acoustic targets. This suggests that they are
398 able to estimate the pitch of a vowel target to a certain extent and to monitor their own vocal source to
399 attempt to get closer to this target. Even more strikingly, they do it even in the convergence task where
400 no explicit imitation instruction was provided – hence the importance to know that all participants
401 performed this task before the “imitative task”, reducing the risk that they could have considered that
402 imitation mattered in the task.

403 Although these results demonstrate that cochlear-implanted patients are able to perceive and imitate
404 the fundamental frequency of the vowel targets, no correlation was however found between their
405 imitative abilities and their auditory discrimination scores in the JND test. This suggests that their
406 imitation abilities are not related to their auditory capacity of perceiving frequencies in a simple way.
407 Nevertheless, cochlear-implanted participants showed less convergence and imitation than adults with
408 normal hearing whatever their age, and higher pitch variability between participants. At this stage, it is
409 unclear if pitch variability in production is due to inaccurate estimation of the target pitch or to
410 degraded voice control, but interestingly, the lack of correlation between convergence and JND
411 suggests that apart from sensory ability, the sensory-motor relationships could differ from one subject
412 to the other. Considering the importance and efficiency of somatosensory control for deaf subjects
413 (Nasir & Ostry, 2008), together with the range of inter-individual variations in the relative importance
414 of auditory and somatosensory control (Lametti et al., 2012; Feng et al., 2011), it is likely that
415 variations in somatosensory dependence could be at hand in these data.

416 Contrary to Blamey et al. (2012) who showed that deafness duration and age at deafness onset are
417 two factors influencing speech perception performance, we did not find any correlation between these
418 factors and CI abilities to imitate or to converge towards an acoustic target. However, it is important to
419 note that in the Blamey et al. study (2012), residual variability not explained by CI- and deafness-
420 related factors was considerable (representing 90% of variation in their study). It seems therefore
421 likely that the limited sample of our CI participants impeded any clear correlation with CI- and
422 deafness-related characteristics to appear in the present study.

423 Finally, contrary to NH participants, CI participant's responses were not always correct (with up to
424 13-15% errors in each task), which suggests some auditory difficulties in the decoding of isolated
425 vowels. Actually, it is known that CI listeners need formant transition to accurately categorize a
426 vowel, as shown by Hanna (2011). The isolated vowels used in our study are hence probably difficult
427 to categorize efficiently by the CI participants. Moreover, convergence effects tested in error trials
428 appear to be similar to those of correct trials, which suggests that timbre and pitch estimations seem to
429 be relatively independent for CI participants. Nevertheless, the major result of this study is that a
430 number of CI participants have already recovered a good ability to associate auditory with motor
431 parameters even a short time after implantation (with significant convergence after only one, two or
432 three months of implantation for some subjects). Indeed, results displayed both automatic and
433 conscious imitation abilities in post-lingually deaf cochlear-implanted patients, displaying their ability
434 to adapt their production to the environment, which is uniquely due to a functional sensory-motor
435 linkage. This should be crucial for the retuning of their speech production system (see Perkell, Lane,
436 Svirsky, & Webster, 1992), enabling them to improve their internal model (Perkell et al., 2000).
437 Interestingly, recovering perceptuo-motor abilities could also be of importance for their speech
438 perception abilities, considering the proposals about the role of the motor system in speech perception
439 (e.g. Skipper, vanWassenhove, Nusbaum, & Small, 2007; Schwartz, Basirat, Ménard, & Sato, 2012).

440

441 **5. Conclusion**

442 The present study reports convergence and imitation abilities in adults with normal hearing, both
443 young and elderly, and in cochlear-implanted subjects. Indeed, in the three groups, we obtain

444 significant and generally strong imitation of the acoustic target during a task with explicit instruction,
445 and also convergence effects in a task without direct instruction. These results first confirm that
446 sensory-motor relationships during speech production are still efficient in elderly subjects, with
447 basically no difference with younger ones. Moreover, crucially, we also show for the first time that
448 cochlear-implanted participants have the ability to converge to an acoustic target, intentionally and
449 unintentionally. Therefore, they have recovered significant sensory-motor abilities, which could be
450 crucial for improving both their speech production and speech perception abilities.

451

452

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456

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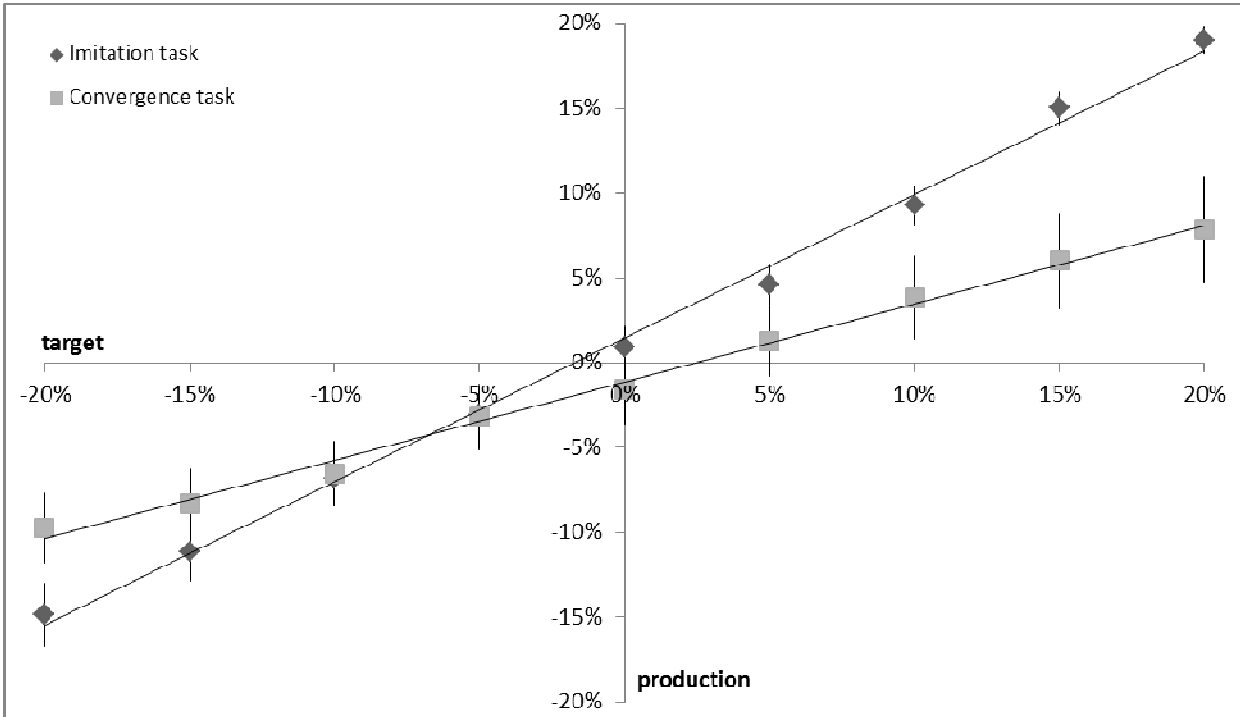
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624 **Figures**

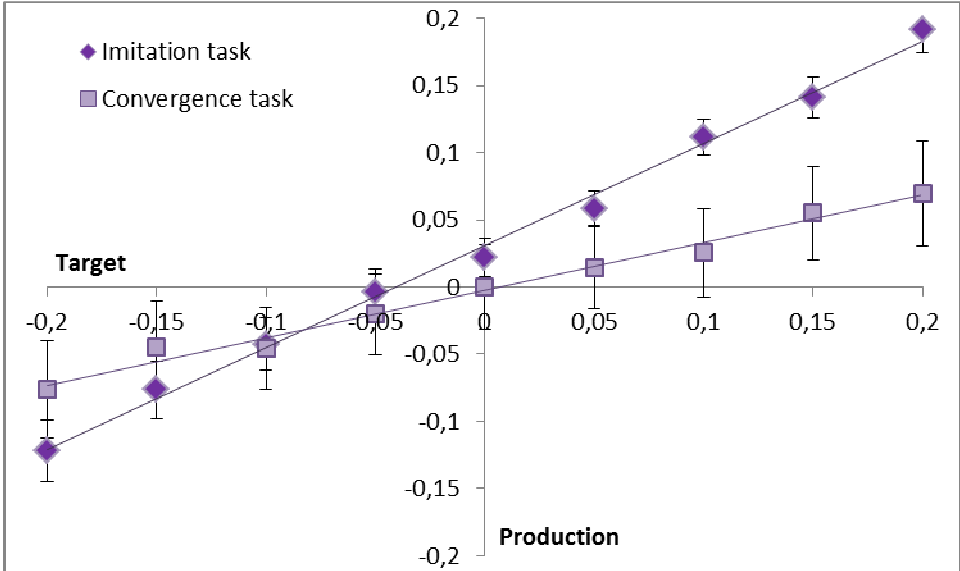
625 Figure 1: Phonetic convergence and voluntary imitative changes on fundamental frequency observed
626 in young participants with normal hearing (X axis: deviation percentage with respect to mean
627 participant' f_0 , Y axis: mean production for all participants, error bars corresponding to standard
628 deviation



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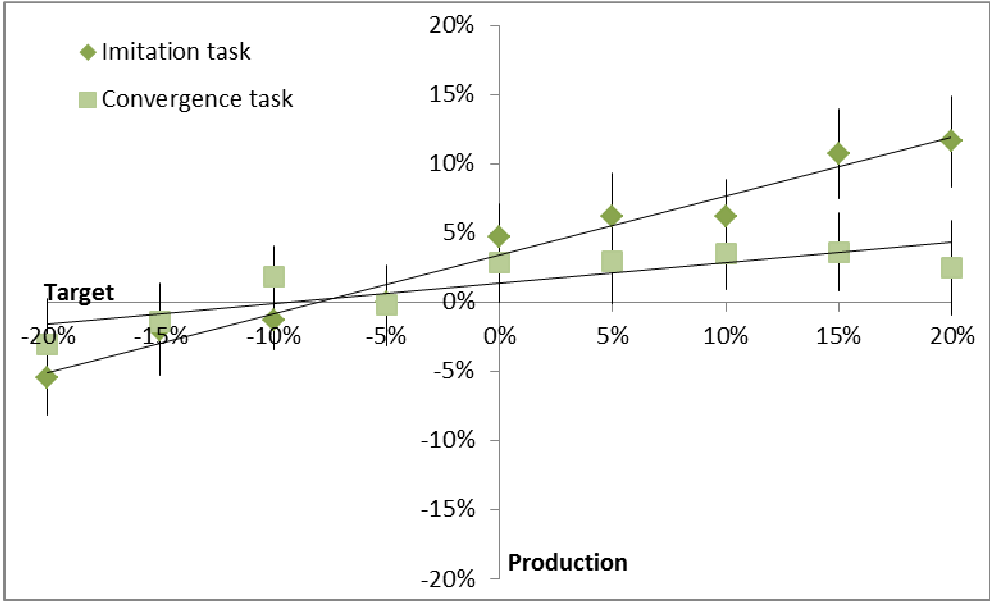
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631
632 Figure 2: Phonetic convergence and voluntary imitative changes observed on fundamental frequency
633 in elderly participants with normal hearing (X axis: deviation percentage with respect to mean
634 participant' f_0 , Y axis: mean production for all participants, error bars corresponding to standard
635 deviation)



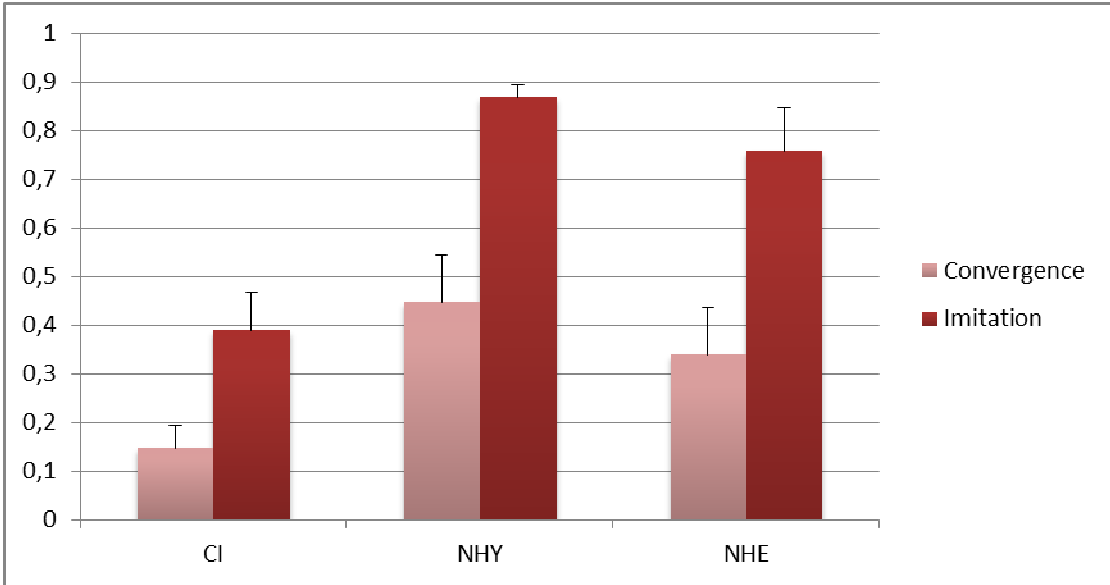
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639 Figure 3: Phonetic convergence and voluntary imitative changes observed on fundamental frequency
640 in cochlear-implanted participants (X axis: deviation percentage with respect to mean participant' f_0 , Y
641 axis: mean production for all participants, error bars corresponding to standard deviation)
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645 Figure 4: Phonetic convergence and voluntary imitative slope changes on fundamental frequency in
646 young (NHY) and elderly (NHE) participants with normal hearing and cochlear-implanted participants
647 (CI) (error bars corresponding to standard deviation)



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654 **Tables**

655 Table 1: Characteristics of participants with cochlear implants

	Gender	Age (y.)	Age at onset of deafness (y.)	Hearing aid	Duration of deafness	Duration of CI experiment
CI1	M	65	7	No	58 years	1 month
CI2	M	56	20	Yes	35 years	3 months
CI3	F	66	32	Yes	25 years	9 years
CI4	M	60	59	Yes	1 month	1 years 4 months
CI5	F	43	20	Yes	13 years	2 months
CI7	M	27	25	Yes	2 months	2 years 6 months
CI8	F	67	65	Yes	2 years	7 months
CI9	M	72	40	Yes	30 years	5 months
CI10	M	76	48	No	27 years	3 years 4 months
CI11	M	57	48	Yes	8 years	10 months

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660 Table 2: Determination coefficients in both tasks for each participant of the cochlear-implanted group
 661 (CI), normal-hearing elderly adults group (NHE) and normal-hearing young adults (NHY). For the
 662 cochlear-implanted group, determination coefficients measured on errors trials only are indicated in
 663 parentheses for participants with at least 15% errors (enabling to obtain a sufficient number of errors
 664 for computing correlations).

CI			NHE		NHY	
convergence	imitation	JND	convergence	imitation	convergence	imitation
0,25 (0,33)	0,51(0,32)	15,22	0,72	0,95	0,96	0,95
0,51	0,70	45,35	0,36	0,28	0,99	1,00
0,78 (0,51)	0,77 (0,73)	1,71	0,98	0,99	0,69	0,99
0,04 (0,17)	0,39	9,76	0,49	0,93	0,99	0,97
0,27	0,94	1,79	0,99	0,96	0,87	0,99
0,12	0,77 (0,41)	4,55	0,88	0,97	0,71	0,91
0,49	0,62	18,52	0,50	0,98	0,05	0,97
0,75	0,92	10,55	0,92	0,98	0,96	0,99
0,11 (0,11)	0,22 (0,03)	16,21	0,99	0,99	0,99	0,99
0,60	0,09	28,54	0,35	0,91	0,10	0,98
					0,95	0,94
					0,98	0,99
					0,84	0,95
					0,63	0,97
					0,97	0,99

665

666

667