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HAL Authorization

1 **Auditory-somatosensory interactions in speech perception in individuals**
2 **with hearing impairment: An exploratory case study**

3 **Monica Ashokumar¹, Jean-Luc Schwartz¹, Takayuki Ito^{1*}**

4 ¹Univ. Grenoble Alpes, CNRS, Grenoble INP, GIPSA-lab, Grenoble, France

5
6 **Corresponding author: Takayuki Ito takayuki.ito@gipsa-lab.grenoble-inp.fr; GIPSA-lab,*
7 *CNRS, 11 Rue des Mathématiques – BP 46, 38402 Saint Martin d’Hères Cedex, France*

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21 **Abstract**

22 **Objectives:** Individuals with hearing impairment can perceive speech sounds with the help of
23 cochlear implants or hearing aids. Recent studies have shown that orofacial somatosensory
24 inputs may modify speech perception. This study explored the potential role of such
25 somatosensory inputs in speech perception in individuals with hearing impairment.

26 **Design:** Twenty-one native-French-speaker participants with various profiles of bilateral
27 hearing impairment and wearing hearing aids and/or cochlear implants were tested to explore
28 the extent to which an orofacial somatosensory stimulation, consisting in facial skin stretch
29 provided by a robotic device, would affect their speech perception performance in a vowel
30 identification task, in comparison with 25 participants with normal hearing. This potential
31 somatosensory effect was evaluated in relation to their hearing ability assessed by both their
32 hearing threshold of digits in acoustic noise and their audiological profile, and with their
33 production ability assessed by variability in a vowel production task.

34 **Results:** The somatosensory effects varied depending on participants' hearing ability, with
35 three different profiles. A first group of eight participants, able to identify the vowels auditorily
36 though with thresholds in noise higher than for individuals with normal hearing, did not show
37 any somatosensory effect, with identical vowel identification scores without and with facial
38 deformation. The other thirteen participants were unable to auditorily identify the vowels and
39 had high thresholds in noise. Among them, eight participants who had used a hearing device
40 for a long duration (≥ 18 years) showed a strong somatosensory bias modifying vowel
41 identification when facial deformation was present. These participants also showed greater
42 variability in vowel production. The last five participants in this second group showed no
43 somatosensory effect at all.

44 **Conclusion:** These three profiles were related to the role of auditory experience and hearing
45 ability in the development of auditory-somatosensory integration.

46

47 **Introduction**

48 Speech perception is generally mostly conceived of as being an audiovisual process where the
49 listener combines visual information from the speaker's face with auditory sounds from the
50 speaker's mouth to perform phonetic identification and ultimately recognize and understand
51 speech (see e.g., Erber, 1971; Grant et al., 1998; Sumbly & Pollack, 1954). However, a number
52 of recent studies suggest that the somatosensory system also seems to intervene in speech
53 perception, by showing that somatosensory inputs related to speech articulatory information
54 may modify speech auditory perception (Ashokumar et al., 2023, 2024; Ito et al., 2009; Ito &
55 Ostry, 2012; Ogane et al., 2020; Trudeau-Fisette et al., 2019). Given that the primary role of
56 the somatosensory system in speech processing is to provide articulatory movement
57 information for speech production, it is likely that the perceptual role of the somatosensory
58 system is mediated by relationships between speech perception and speech production acquired
59 in the course of development, as shown by recent data showing how somatosensory inputs
60 during speech motor learning were involved in the recalibration of speech perception (Ohashi
61 & Ito, 2019). However, no study has yet explored whether the somatosensory effect on speech
62 perception also occurs for participants with hearing deficits, whose speech production and
63 perception develop differently due to auditory deprivation. The question is of importance for
64 both theoretical reasons (to better understand how the somatosensory and auditory systems
65 cooperate in speech perception when development occurs under atypical auditory conditions)
66 and clinical reasons (the somatosensory system could be of interest in the reeducation process
67 for individuals with hearing impairment for both speech perception and speech production). As
68 a first step to address these questions, the current study examined whether and how the speech
69 perceptual modulation due to somatosensory inputs was induced in individuals with hearing
70 impairment. In the following, we present in more detail the somatosensory effect in speech
71 perception, the potential role of developmental factors, the variability in hearing impairment

72 profiles that could be of importance in the somatosensory effect in this population before finally
73 presenting our hypotheses and the plan of this paper.

74

75 *The somatosensory effect in speech perception*

76 Somatosensory inputs related to proprioception by providing movement information have been
77 shown to modify the perception of corresponding speech sounds in a systematic way (Ito et al.,
78 2009). This study used facial skin stretch as somatosensory stimulation based on the findings
79 that orofacial cutaneous mechanoreceptors can provide movement information for facial
80 movements including speech (Connor & Abbs, 1998; Johansson et al., 1988), and that the
81 deformation of facial skin specifically provides articulatory movement information in the
82 stimulated direction (Ito & Gomi, 2007; Ito & Ostry, 2010). As a potential consequence, in a
83 vowel identification task contrasting ‘head’ and ‘had’, it was shown that when the facial skin
84 was deformed in the upward direction during the presentation of ambiguous sounds, the
85 participants perceived ‘head’ rather than ‘had’. The opposite change was found to occur when
86 the facial skin was deformed in the downward direction and disappeared when the facial skin
87 was deformed in an irrelevant direction (backward).

88 The synchronization pattern between sounds and facial deformation is crucial in this effect.
89 Indeed, the effect was present when the temporal pattern of stimulation was similar to the
90 pattern observed in the actual production of vowels, with a somatosensory onset set to precede
91 the auditory onset by 90 ms, but not when the facial skin was statically deformed. In a similar
92 way, Masapollo & Guenther (2019) showed that a static somatosensory perturbation only
93 influenced visual perception of vowels if the visual presentation involved dynamically
94 articulating faces. The precise temporal offset between sound and facial deformation is
95 important. This is supported by the finding from Ito et al. (2014), who showed that the EEG

96 cortical potentials in response to the combined auditory-somatosensory stimulation used in Ito
97 et al. (2009) varied depending on the temporal relationship between the two modalities (90 ms
98 lag, 90 ms lead, and simultaneous presentation). The timing of somatosensory stimulation
99 relative to the auditory sounds was also found to be crucial in a lexical decision task related to
100 word segmentation (Ogane et al., 2020).

101 These results show that movement information related to a given speech articulatory task and
102 received from somatosensory inputs changes speech perception of the corresponding
103 productions accordingly, provided that there is a spatio-temporal correspondence between
104 somatosensory inputs and speech gestures underlying the presented sounds. Moreover, Patri et
105 al. (2020) showed that vowels can be identified based on somatosensory information alone.
106 They used a tongue-positioning task where the participants had to position their tongues to the
107 target postures related to vowels (which were visually guided on a monitor) in a protocol that
108 meant that the corresponding configuration was never visually represented. Without any
109 auditory inputs or visual cue, and without any indication about the vowels corresponding to the
110 presented target posture, the participants were able to categorize the vowels only based on their
111 tongue posture.

112 And, conversely, speech sounds affect orofacial somatosensory perception, as shown by Ito &
113 Ostry (2012) who used a task in which subjects had to evaluate the amplitude of a facial skin
114 deformation applied in synchrony with the production of a vowel that shared articulatory
115 characteristics with the deformation. Altogether, this shows that the somatosensory system does
116 intervene in the multisensory integration process in speech perception which leads to the
117 construction of auditory-somatosensory (and probably auditory-somatosensory-visual)
118 representations of speech inputs. This is in line with theoretical proposals on the involvement
119 of speech production representations in speech perception and more globally on a cognitive link
120 between perception and production mechanisms (Fowler, 1986; Liberman & Mattingly, 1985;

121 Schwartz et al., 2012; Skipper et al., 2007). In this framework, the somatosensory system may
122 play an important role (see a review in Franken et al., 2022) in providing information on speech
123 production information in the speech perception process. Crucially, the current somatosensory
124 stimulation associated with facial skin deformation enables the investigation of the
125 somatosensory function in the processing of speech sounds in the absence of any motor
126 contribution. The modulation of the speech perception output by a synchronous somatosensory
127 input can be used as an index of the somatosensory involvement in speech perception. In the
128 current paper, we referred to this perceptual modulation due to movement-related
129 somatosensory inputs as “somatosensory effect in speech perception”.

130

131 ***Potential insights on the development of the somatosensory effect in speech perception in***
132 ***relation to handicap***

133 Taking into account the close relationships between speech production and perception abilities
134 (Chao et al., 2019; Franken et al., 2017; Ghosh et al., 2010; Perkell et al., 2004), and considering
135 that combined auditory-somatosensory inputs are received by human speakers in online speech
136 production and throughout its development, it has been suggested that the relationships between
137 sounds, somatosensations and gestures are acquired in the course of speech development
138 (Franken et al., 2022; Guenther, 2006). In consequence, the somatosensory effect in speech
139 perception could also be related to the performance or development of speech production.
140 Indeed, Ashokumar et al., (2023) showed that the amplitude of the somatosensory effect in
141 speech perception was correlated with the production performance for corresponding speech
142 sounds. Their study exploited a vowel identification task between two French vowels, the front
143 mid-high vowels /e/ vs. /ø/ (respectively unrounded and rounded), and showed that backward
144 skin stretch perturbation, which can be related to the production of /e/, modified the perception

145 towards /e/. The amplitude of perceptual modulation among participants was found to correlate
146 with the amplitude of the acoustic contrast between the two vowels in production. The latter is
147 the acoustical distance in the second formant of the target vowels, which is the primary formant
148 contributing to the acoustic contrast between /e/ and /ø/. Using the same combination of
149 somatosensory stimulation and vowel identification between /e/ and /ø/, Trudeau-Fisette et al.
150 (2019) showed that children also display auditory-somatosensory integration, albeit to a lesser
151 extent than adults. This is also in line with the view that the development of multisensory
152 integration in speech perception could occur along with the accumulation of sensory
153 experiences over time (Gori, 2015).

154 Regarding individuals with hearing impairment, the question is to understand how a
155 degradation of auditory inputs during the development of speech production and perception
156 influence auditory-somatosensory integration. For the acquisition of these two functions,
157 individuals with hearing impairment require the help of hearing devices in most cases. If speech
158 production is mastered properly with the help of hearing devices, it is likely that the ability to
159 integrate sounds and somatosensory stimulations in speech perception could also be acquired
160 in a more or less similar way to normal hearing individuals. In contrast, an imperfect or
161 incomplete mastery of speech production should modify the role of the somatosensory system
162 in speech perception. Moreover, the effect should depend on auditory perception per se.
163 Accordingly, we conjecture that, if this somatosensory effect exists, it should vary depending
164 on an individual's hearing profile or, more specifically, type of hearing device, age of
165 implantation, and duration of a device usage, and be in some way also related to the production
166 abilities involved.

167

168 *Variability in hearing impairment profiles*

169 Individuals with hearing impairment can enhance their acquisition and maintenance of speech
170 perception and production performance with the help of external devices: cochlear implants
171 and/or hearing-aids. Specifically, in the case of congenitally deaf individuals, the impact of
172 hearing loss on speech production can be greatly reduced when they receive auditory inputs
173 before a certain critical period (Kral & Eggermont, 2007; Kral & Sharma, 2012). Although the
174 usage of those hearing devices enables the acquisition of speech perception and production to
175 a sufficient extent for daily life, precise evaluation by experimental tools reveals some departure
176 from performance in normal-hearing individuals. Thus, Bouton et al. (2012) showed that deaf
177 or hard-of-hearing children with cochlear implants displayed lower accuracy in both their
178 categorization and their discrimination of various kinds of phonetic contrasts than normal-
179 hearing children of the same listening age, i.e., the same duration of listening experience.
180 Speech perception abilities in individuals with hearing impairment vary depending on various
181 factors such as age of implantation (Waltzman & Cohen, 1998), type of hearing device (Mildner
182 et al., 2006), their duration of usage (Bernhard et al., 2021), and cognitive factors (Pisoni, 2000).
183 In a recent review of the literature on the benefits of cochlear implantation in children, (Sharma
184 et al., 2020) show that very early implantation, possibly between 6 and 18 months and crucially
185 before 3 years of age, largely improves the speech perception performance, with the possibility,
186 for the best cases and with early enough implantation, to reach quasi normal performance in
187 both speech perception and production. Still, variations in performance may actually be quite
188 large - ranging from quite good to quite poor - as was analyzed in detail in a scoping review of
189 developmental influences other than age of implantation (Corbett & Van Zalk, 2025). Apart
190 from the afore-mentioned factors, another cause of deterioration in hearing ability is aging
191 which could also lead to differences in speech perception and production outcomes. As a result,
192 there is altogether a large variety of hearing profiles within individuals with hearing impairment

193 and this variety of profiles may lead to a variety of profiles in their speech perception and
194 production abilities.

195 The development of the perception-production link has also been extensively studied in
196 individuals with hearing impairment (Blamey et al., 2001; O'Donoghue et al., 1999; Tye-
197 Murray et al., 1995). If exposure to speech is missed during the critical period mentioned above,
198 individuals with hearing impairments can lose the possibility to acquire a typical level of
199 hearing and fluent speaking (Cardon et al., 2012). As a result, the acquisition of perception-
200 production link could also be impaired. Tye-Murray et al. (1995) showed that children using
201 cochlear implants who had a better level of perception of target speech features (voicing,
202 nasality, duration, frication, and place of articulation) also displayed better intelligibility in
203 production, and also that the production performance was related to the duration of experience
204 of cochlear implant. O'Donoghue et al. (1999) carried out a prospective study with profoundly
205 deaf children at different stages of cochlear implantation such as pre-implantation, 2, 3, 4, and
206 5 years post-implantation. They showed that early speech perception abilities can affect later
207 speech production skills, specifically speech perception abilities, as early as two years post-
208 implantation which seemed to predict speech production in the three, four- or five-years post-
209 implantation. All these studies converge to show that early sensorimotor experience is
210 important in the development of speech communication including acquisition of the perception-
211 production link.

212

213 *Hypotheses and objectives of the present study*

214 We can in fact make several different conjectures as to how auditory-somatosensory
215 interactions could occur in individuals with hearing impairment. A first baseline hypothesis
216 could be that if their audition is sufficiently well corrected by hearing devices, the

217 somatosensory inputs would affect speech perception in a similar way to normal hearing
218 individuals. Still, two other hypotheses could modify this baseline. Firstly, when considering
219 the degraded quality of speech sounds provided by a hearing device, participants with hearing
220 impairment might rely more on somatosensory inputs in speech perception to compensate for
221 poorer hearing abilities. This would be in line with the 'inverse effectiveness' principle by which
222 multisensory enhancement is greater if a given sensory input is degraded (Stein & Meredith,
223 1993; van de Rijt et al., 2019), as indeed seems the case for visual effects on auditory speech
224 perception in individuals with hearing impairment (Desai et al., 2008; Rouger et al., 2008;
225 Schorr et al., 2005). Conversely, attentional mechanisms could intervene in auditory-
226 somatosensory integration, as is the case for vision in audio-visual integration. Indeed, despite
227 the classical assumption that the McGurk effect in audio-visual integration (McGurk &
228 MacDonald, 1976) is automatic, it has been shown that the size of the McGurk effect was
229 drastically decreased when the participants were concurrently performing an unrelated task, be
230 it auditory, visual (Alsius et al., 2005) or tactile (Alsius et al., 2007), and interpreted as showing
231 that integration may decrease or fail under attentional pressure. Though the role of attention in
232 auditory-somatosensory interactions has not been previously studied to our knowledge, it could
233 be posited that more attention might be needed from participants with hearing impairment in
234 the listening process, resulting in lesser involvement of auditory-somatosensory interactions.
235 This may be in line with the finding by Lachs et al. (2001) showing lesser usage of audio-visual
236 information in prelingually deaf children with cochlear implants and lower hearing ability.
237 Finally, considering the role of developmental processes associated to speech production
238 performance in auditory-somatosensory interactions, the lack of proper auditory inputs
239 resulting in a degraded hearing experience during developmental periods and poorer speech
240 production performance, may have interfered with the learning processes necessary for the
241 development of somatosensory interactions in speech perception. To sum up then, performance

242 in speech production might predict to a certain extent the somatosensory effect in speech
243 perception in individuals with hearing impairment.

244 The focus of the present paper was precisely to explore auditory-somatosensory interactions in
245 individuals with hearing impairment and assess whether any of these possibilities might be
246 consistently observed in any type of individuals with hearing impairment, depending on their
247 hearing profile (including type of hearing device and duration of experience with this device),
248 and in relation with their production performance. Due to the lack of previous research in this
249 field, the current study is purely exploratory in nature. Considering the known large variability
250 in hearing profile and speech perception performance in individuals with hearing impairment
251 as mentioned previously, we assumed that this form of exploration of auditory-somatosensory
252 interactions could enable the assessment and testing of the various predictions outlined above.

253 To work towards this stated aim, we assessed whether the somatosensory effect in speech
254 perception can be found in individuals with hearing impairment and how the effect is related to
255 their hearing profile. To study participants who are native speakers of French, we applied the
256 paradigm first used in Trudeau-Fisette et al. (2019) who tested Canadian French speakers. The
257 experimental paradigm exploits a vowel identification task using a speech continuum between
258 two front mid-high French vowels, the lip-spread vowel /e/ vs. lip-rounded vowel /ø/, which
259 mainly present an acoustical contrast in the second formant (F2). Considering that these two
260 vowels are articulatorily contrasted by horizontal labial gestures — specifically, 'spread' versus
261 'rounded' lips — the somatosensory stimulation associated with facial skin stretch was applied
262 in the horizontal backward direction which could be associated with the production of /e/. The
263 target somatosensory effect in speech perception was quantified as the difference in judgment
264 probability between vowel auditory categorization scores with and without somatosensory
265 stimulation. By testing participants with partial or complete hearing impairment and with
266 variable use of hearing devices (cochlear implants and/or hearing aids), we examined whether

267 and how the somatosensory effect in speech perception was related to their basic hearing
268 performance represented by hearing thresholds in noise screened in a separate test, and to their
269 hearing profile. Considering the potential role of the relationship between speech production
270 and speech perception in this effect, we also evaluated their production performance. Since
271 precision in production is considered as a key feature degraded in speakers with hearing
272 impairment (e.g. Turgeon et al., 2020), we assessed production by evaluating the participants'
273 variability in the production of the corresponding vowels /e/ and /ø/, and examined whether
274 there is a consistent tendency between variability in speech production and size of the
275 somatosensory effect. The analysis of experimental data followed an exploratory case study-
276 style protocol, in which we attempted to design post-hoc different profiles of participants based
277 on the distribution of both perceptual and production performance, and corresponding hearing
278 profiles.

279

280 **Methods**

281 *Participants*

282 We tested twenty-five individuals with normal-hearing (NH, aged 18-31) and twenty-one
283 individuals with bilateral hearing impairments wearing hearing-aids and/or cochlear implants
284 (HI, aged 18-74). In the HI group, two participants were diagnosed as displaying mild to
285 moderate hearing loss (P01 and P02) and the rest are characterized as showing severe to
286 profound hearing loss. Since our aim was to conduct exploratory testing with a variety of
287 participants with hearing impairment who use hearing devices, we did not conduct testing with
288 an age-matched control group. Instead, we recruited a group of young adult participants alone
289 as controls to obtain a pattern of auditory-somatosensory interaction effect considered typical
290 in the current experimental environment. Participants of both groups were native French

291 speakers and participated in the same experimental procedure. The main experimental
292 procedure was a vowel identification test with somatosensory stimulation. We assessed the
293 hearing threshold through a task of detection of uttered digits embedded in acoustic noise, and
294 the speech production ability by evaluating the variability in the production of the
295 corresponding vowels.

296 In addition to this, participants in HI were asked to fill out a hearing assessment questionnaire
297 to obtain information about their hearing profile such as the onset of deafness, the hearing-
298 devices used and the duration of the usage thereof. This information is presented graphically
299 for each participant in Figure 3b, together with experimental data which will be presented in
300 the Results section. In this panel, the entire length corresponds to the participant's age. The
301 white area provides the period before the detection of hearing impairment, showing that 13
302 participants were detected before the age of 5 and hence were very likely to present a congenital
303 deafness/impairment, while impairment was acquired at various ages, from young to adult or
304 senior, for the 8 others. The black area displays the duration of non-use of any hearing device
305 after the detection of hearing loss. The light grey and striped gray areas respectively represent
306 the duration of using a hearing-aid or a cochlear implant in either one or both ears. All
307 participants in HI were able to speak in a way enabling smooth oral communication, as
308 informally checked during conversations before the experimental procedure. All the
309 participants signed the consent form approved by the local ethical committee of the Université
310 Grenoble Alpes [Comité d'Ethique pour la Recherche, Grenoble Alpes (CERGA-Avis-2021-
311 8)].

312

313 *Experimental setup and sensory stimuli*

314 The study was carried out in a sound-proof room to reduce the effects of environmental noise.
315 The participants were seated in front of a computer monitor, a loudspeaker (Behritone C50A)
316 and a microphone (AKG C1000B). For the presentation of auditory stimuli, to ensure that the
317 participants in HI could comfortably listen to the stimuli without having to adjust their hearing
318 devices, we used a loudspeaker instead of the headphones we used in our previous studies
319 showing somatosensory effects in speech perception (Ito et al., 2009; Ogane et al., 2020;
320 Trudeau-Fisette et al., 2019). The stimulus sound was presented at a level similar to usual
321 conversation and fixed in all participants. A robotic device (Phantom Premium 1.0, SensAble
322 Technologies) was placed behind the participants as shown in Figure 1. The participant was
323 connected to the robotic device with thin thread at the lateral side of the mouth. This site was
324 selected based on the study by Ito & Gomi, (2007) and has been consistently used for previous
325 studies using stimulation associated with facial skin deformation (Ashokumar et al., 2023,
326 2024; Ito et al., 2009, 2014; Ito & Ostry, 2010, 2012; Ogane et al., 2020; Trudeau-Fisette et al.,
327 2019). This configuration enables the application of facial skin stretch in a backward direction
328 for somatosensory stimulation. In the target vowels /e/ and /ø/, this backward stretch is
329 consistent with lip spreading which is involved in the production of /e/, and opposite to lip
330 compressing involved in the production of /ø/.

331 For the auditory tasks, we applied two sets of acoustic stimuli. The first set was used in the
332 main vowel categorization test assessing the somatosensory effect in speech perception. We
333 used an acoustic continuum between two front mid-high French vowels, the lip-spread vowel
334 /e/ and lip-rounded vowel /ø/. The detail of the generation of the continuum is described in
335 Trudeau-Fisette et al. (2019). Briefly, the continuum was generated by an articulatory
336 synthesizer based on Ménard & Boë (2004). It comprised eight 300-ms stimuli with fixed
337 formant values along each stimulus. The formants F1 and F5 were kept constant for the eight
338 stimuli in the continuum (364 Hz and 4000 Hz respectively) while F2, F3 and F4 were equally

339 shifted in steps of 30, 40 and 50 Hz respectively from one stimulus to the next so that extreme
340 configurations corresponded to values typical for /e/ at one end (F2 = 1922 Hz, F3 = 2509 Hz,
341 F4 = 3550 Hz) and for /ø/ at the other end (F2 = 1712 Hz, F3 = 2229, F4 = 3200 Hz).

342 The second set of acoustic stimuli was used in the test measuring the hearing threshold in noise.
343 We applied monosyllabic French digits (1 to 9) following a prefixed carrier phrase “les
344 numéros” (“The numbers” in English), recorded by a French female speaker (French DTT Digit
345 Triplet Test material, details in Jansen et al., 2013). Each digit sound was embedded in a
346 stationary speech-shaped noise. The background noise started 500 ms before and stopped
347 500 ms after the stimulus. In the test, the noise level was fixed at 70 dB SPL and the signal-to-
348 noise ratio (SNR) of the stimulus sound was controlled by the participant’s response using the
349 adaptive procedure presented below.

350 For the somatosensory stimulation, we applied a force following the first half of a sinusoidal
351 pattern with a peak force of 4N in the backward horizontal direction, which can correspond to
352 the articulatory movement for the lip-spread vowel /e/. We set a 90-ms lead of the
353 somatosensory stimulation relative to the onset of the auditory stimuli as this temporal
354 coordination successfully altered speech perception in previous studies (Ito et al., 2009, 2014).

355

356 *Experimental procedure and data analysis*

357 The participants in HI were asked to complete the questionnaire before the tests. Then all
358 participants (NH and HI) first carried out the vowel identification task with somatosensory
359 stimulation. After removing the setup for somatosensory stimulation, they were presented with
360 the hearing-in-noise test and the vowel production task in order. All tests, along with the
361 questionnaire for the participants in HI, were completed within one hour. The details of each
362 test and analysis are provided below.

363 The target vowel identification test followed a forced-choice procedure similar to the one used
364 in Trudeau-Fisette et al. (2019). The participants were asked to categorize the vowel presented
365 from the /e/-/ø/ continuum as either /e/ or /ø/, by pressing a key on the keyboard. Each of the
366 eight members of the /e/-/ø/ continuum were randomly presented every eight trials. We tested
367 two conditions: auditory only (CTRL) and auditory-somatosensory (SOMA). The two
368 conditions were alternated every eight trials. In total, 192 trials (24 blocks of 8 trials) were
369 tested. We calculated the probability of judging the sound as /e/ for each member of the
370 continuum, in each condition and for each participant. The vowel identification performance
371 was assessed by considering the obtained judgment probability across the stimulus continuum.
372 As found in Trudeau-Fisette et al., (2019), we expected that the participants in the SOMA
373 condition with somatosensory stimulation would perceive more /e/ and hence that the /e/-
374 judgment probability would increase compared with the CTRL condition without
375 somatosensory stimulation. Importantly, it was not possible to apply psychometric function
376 fitting to the participants' judgments to evaluate and compare perceptual boundary measures
377 between conditions, since many participants in HI did not exhibit the typical sigmoid pattern of
378 vowel identification responses, as will be discussed in the Results section. Hence, to evaluate
379 the perceptual change associated to the somatosensory stimulation, we computed the mean
380 judgment probability taking an average across the stimulus continuum for a given participant
381 in each condition and defined the perceptual shift as the modification of this mean /e/ score
382 from the CTRL to the SOMA condition. This measure presents the interest to group a
383 modification to the boundary in a single value if the psychometric curve for the continuum is
384 indeed a sigmoid, or a global increase or decrease of the /e/-probability if the psychometric
385 curve is flat. Considering the relatively large noise in the response in HI, the current measure
386 of averaged judgment probability reflects the participants' responses better than an
387 approximated measure by psychometric function fitting.

388 Changes in this mean judgment probability value were statistically evaluated by a repeated-
389 measures ANOVA applied between the SOMA and CTRL conditions. Although we divided
390 our participants into three groups as will be discussed in the Results section, we did not apply
391 group comparison due to several limitations of our dataset in the context of this exploratory
392 case study: grouping based on post-hoc analysis; a relatively small number of participants in
393 each group; differences in basic performance in speech vowel perception across groups;
394 differences in the effect size. As a result, ANOVA was separately applied in each group just for
395 quantitative assessment of the target somatosensory effect in the vowel identification task.

396 For the evaluation of hearing ability, we applied the French Digit triplet test (Jansen et al., 2010)
397 instead of using the conventionally-used pure-tone audiometry to evaluate hearing ability in a
398 speech context and in a relatively short experimental time with a computer-controlled
399 procedure. The outcomes from the Digit-triplet test show a good level of repeatability with
400 reproducible scores from one evaluation to the next in a given participant (Smits et al., 2004)
401 and also strongly correlate with pure-tone audiometric thresholds (Potgieter et al., 2018) and
402 other speech-in-noise measures (Smits et al., 2004). For these reasons, in our view the Digit-
403 triplet test was an appropriate alternative to pure-tone audiometry for the current test. In the
404 test, the participants were asked to identify what digit was presented by pressing a numeric
405 keyboard. The SNR was adjusted in every trial based on the participants' response. A large
406 variability of hearing threshold in noise was expected in the participants in HI so we modified
407 the procedure by dividing the test into two parts which also enabled the test to be completed
408 with a fixed number of trials. A digit-singlet phase for rough estimation with large SNR (4 dB)
409 steps was followed by a digit-triplet phase for detailed search with small SNR (1 dB) steps as
410 shown in Figure 2. In the digit-singlet phase, single French digits (1-9) were presented in ten
411 trials in a pseudo-random order. We started from 0 dB SNR and changed the SNR every trial
412 based on a simple up-down procedure with 4-dB steps. Based on our empirical observation that

413 the responses converged after four trials in most of the participants as shown in the example in
414 Figure 2, we took an average of the SNRs in the last six trials for a rough estimation of the
415 hearing threshold. The averaged trials are represented by the thick black line in the left part of
416 Figure 2. The obtained value was used as the initial value in the following digit-triplet phase.
417 The procedure of this digit-triplet phase was similar to the one in Jansen et al., (2013). Twenty-
418 seven predetermined triplets were presented in a pseudo-random order. The SNR was decreased
419 in 1-dB steps when all three digits were correctly identified and increased by 1 dB if there was
420 at least one incorrect response (with a ceiling value at 0 dB SNR). The test was carried out until
421 the participants responded to all 27 triplets. The hearing thresholds in noise were obtained by
422 averaging the last seventeen SNRs (the black thick line on the right part of Figure 2).

423 Speech production performance was assessed by the standard deviation (SD) of acoustic
424 utterances in the production of the target vowel sounds /e/ and /ø/. In the test, we recorded the
425 vowels embedded in a CV word, “dé” (English “dice,” /de/) and “deux” (English “two,” /dø/),
426 rather than these being isolated, with the intention of making the test more natural and familiar
427 for the participants. The participants were asked to utter the word when the corresponding
428 picture was shown on the monitor. The task was carried out in a pseudo-random order. We
429 recorded six repetitions for each vowel. It should be noted that that this production session was
430 originally designed to record the whole set of French oral vowels. Considering the total
431 experiment time, we limited the number of repetitions in each vowel category to six. In off-line
432 analysis, F1, F2 and F3 frequencies were computed by PRAAT (Boersma & Weenink, 2001)
433 and were temporally averaged within a 40-ms time window centered on the middle of the vowel
434 production period. The onset and offset of the vowel production period were manually detected
435 with visual inspection. The formants obtained for each utterance and each participant were
436 normalized by division by the mean of the six values of the corresponding formant for the
437 participant and for the corresponding vowel. We calculated SD and averaged it across the two

438 target vowels for each formant F1, F2 and F3 and each participant. One-way ANOVA with
439 post-hoc analysis using Tukey's HSD test was applied in each formant across the groups that
440 will be defined later. Given that F2 and partly F3 but not F1 are associated to the rounding
441 acoustic contrast in the current stimulus pair /e/-/ø/, we compared each formant F2 and F3
442 separately to assess differences in formant frequency across vowel categories. This is also based
443 on our previous findings (Ashokumar et al., 2023, 2024) whereby the effect of horizontal skin
444 stretch was prominent in F2 and partly F3, but not in F1.

445

446 **Results**

447 We will first report the results from the participants with normal hearing (NH). Their hearing
448 thresholds reached $-8.5 \pm .1$ dB SNR. This level is slightly higher than the thresholds obtained
449 in previous studies: $-10.5 \pm .3$ dB SNR in French participants (Jansen et al., 2010) and $-11.2 \pm$
450 1.3 dB SNR in Dutch participants (Smits et al., 2004). This was probably due to differences
451 both in stimulus presentation environment (headphones in Jansen et al. (2010), vs. telephone in
452 Smits et al. (2004), vs. loudspeaker here) and SNR evaluation (systematic evaluation of the
453 psychometric function in Jansen et al. (2010), vs. adaptive procedure in Smits et al. (2004) and
454 in the present study).

455 Considering the vowel identification task, we successfully replicated the results from Trudeau-
456 Fiset et al. (2019) about the somatosensory effect in this task. The results averaged across
457 participants are shown in the top panel of Figure 4. As shown here, NH participants identified
458 the vowels in the typical sigmoidal portrait for a vowel categorical identification task in the
459 auditory-only condition (CTRL). In the condition with somatosensory stimulation, the
460 perceptual boundary between /e/ and /ø/ shifted slightly towards /ø/, indicating that the NH
461 participants identified more sounds as /e/. Repeated-measures ANOVA showed a significant

462 increase in judging the vowel as /e/ in the SOMA condition ($F(1,24) = 6.7, p = .02, \eta p^2 = .22$).
463 Hence, as shown in our previous study (Ashokumar et al., 2023), the somatosensory effect in
464 speech perception can be consistently induced in the current open-air situation using a
465 loudspeaker rather than headphones.

466 Let us now describe the results for the participants in HI. Their performance was quite varied
467 in both the vowel identification test and the hearing threshold screening. Figure 3 summarizes
468 those results in the two perception tests together with the hearing profile for each participant in
469 the HI group. This figure is organized around two criteria that we considered likely to allow
470 different portraits of participants in HI to emerge. Firstly, their ability to categorize the vowels
471 auditorily is more or less directly related to their hearing thresholds, and secondly, the
472 somatosensory effect in speech perception only seems to appear for specific profiles of
473 participants with hearing impairment.

474 For the first criterion, the vowel identification performance visible in Figure 3c (black dots and
475 lines) shows that more than half of participants in HI (13 of 21, from P09 to P21) were not able
476 to identify the vowels correctly in the auditory-based condition (without somatosensory
477 stimulation). Indeed, they mostly showed a flat pattern of judgment probabilities across the
478 stimulus continuum. We categorized those thirteen participants as a second group HI-2
479 contrasting them with a first group HI-1 of eight participants (P01 to P08). Participants in this
480 first group HI-1 displayed more or less sigmoidal patterns of auditory classification
481 progressively switching from one category to the other, particularly for some participants (P01,
482 P02, P05 and P07) who showed patterns similar to those of NH participants, while some others
483 still showed some difficulty in identifying the vowels.

484 These patterns of auditory categorization seem rather well related to the participants' hearing
485 threshold in noise displayed in Figure 3a. Indeed, most participants in HI-2 (with two

486 exceptions) showed a high hearing threshold in noise (≥ 0 dB SNR). On the other hand,
487 participants in HI-1 showed relatively low hearing thresholds between -7 and -1 dB SNR,
488 though still higher than those of NH participants ($-8.5 \pm .1$ dB SNR, displayed by the vertical
489 solid line in the figure). It therefore appears that a sufficiently low hearing threshold in noise
490 can be required to identify the vowels correctly which is in line with the general idea that a
491 minimal hearing ability is required to adequately capture the sound characteristics. The two
492 clearest cases are provided by participants P01 and P02 who have mild to moderate hearing
493 loss, and who showed the two lowest hearing thresholds and the steepest identification curves
494 within the group.

495 For the second criterion, we shall consider the amount of the somatosensory effect that was
496 qualified as a change of judgment probabilities between auditory-somatosensory (SOMA) and
497 auditory-alone (CTRL) conditions in Figure 3c (red vs. black dots and lines). It appears that,
498 while the participants in HI-1 were able to identify the vowels in a relatively correct way, they
499 did not show any clear differences between the two conditions. However, a strong perceptual
500 bias due to the somatosensory stimulation was seen in several participants in HI-2. We further
501 divided HI-2 into two sub-groups. Eight participants who showed a perceptual bias were
502 grouped in HI-2b and the others in HI-2a. The participants in HI-2b all displayed judgment
503 probabilities in the SOMA condition that were much higher than their counterparts in the CTRL
504 condition. This indicates that the participants perceived the stimulation more as /e/ when the
505 somatosensory stimulation was applied. In contrast, participants in HI-2a showed no clear
506 difference between conditions. The pattern relating auditory threshold in noise (SNR) to
507 amplitude of the somatosensory effect is displayed in Figure 5, in which the summary data (the
508 dispersion ellipses (95% confidence intervals) for each group separately) show that there is no
509 clear relationship between both. Still, the two sub-groups HI-2a and HI-2b have a clear
510 difference in their hearing profile. Indeed, Figure 3b displays the participants' hearing profile

511 over their lifetime. For each participant, the entire length of the bar corresponds to the age. The
512 gray and striped gray parts represent the duration of the usage of hearing devices. The gray part
513 corresponds to hearing-aids and the striped gray part corresponds to cochlear implants. The
514 black part represents the duration without a hearing device after the detection of hearing-
515 impairment. It appears that participants in HI-2a were all elderly (> 55 years) with most of them
516 diagnosed post-lingually. In contrast, participants in HI-2b were diagnosed pre-lingually and
517 had a long duration of usage of a hearing device (≥ 18 years).

518 This division in three groups is summarized in Figure 4 which displays the patterns of responses
519 in the CTRL and SOMA conditions averaged separately over the participants of the three
520 groups, compared with those of the NH participants. The patterns are rather coherent and clearly
521 display the different behaviors of the participants in these groups. Repeated-measures ANOVA
522 applied separately in each group showed no difference between the conditions in HI-1 ($F(1,7)$
523 $= 1.3$, $p = .3$, $\eta p^2 = .16$) nor in HI-2a ($F(1,4) = .3$, $p = .6$, $\eta p^2 = .06$). However, participants in
524 HI-2b showed a strongly significant difference between CTRL and SOMA ($F(1,7) = 74.9$, p
525 $< .001$, $\eta p^2 = .91$).

526 Additionally, we assessed the variability in the production performance in each of the 4 groups
527 (including NH). Figure 6 shows the standard deviation (SD) for each formant in each group.
528 The mean SD was significantly different across groups in F1 ($F(3,42) = 2.8$, $p = .0493$, $\eta^2 =$
529 $.17$) and in F2 ($F(3,42) = 12.4$, $p < .001$, $\eta^2 = .47$), but not in F3 ($F(3,42) = 2.6$, $p = .07$, $\eta^2 =$
530 $.16$). Post-hoc analysis with Tukey's HSD showed a significant difference in F1 between HI-
531 2b and NH ($z = -.03$, $p < .05$) and in F2 between HI-2b and the other three groups, respectively:
532 HI-1 ($z = .02$, $p < .001$), HI-2a ($z = .03$, $p < .001$) and NH ($z = -.03$, $p < .001$). Hence it appears
533 that participants in HI-2b showed a greater variability in production, particularly in F2,
534 compared with the other three groups, while those of the other HI groups (HI-1 and HI-2b)
535 showed a similar variability to NH.

536

537 **Discussion**

538 In the current study, we examined the role of somatosensory inputs in speech perception in
539 individuals with hearing-impairment. This was assessed in the context of the change in vowel
540 identification performance due to somatosensory stimulation. We based our approach on the
541 finding in Trudeau-Fisette et al. (2019) that the addition of a backward somatosensory
542 perturbation in an auditory vowel identification test between the French vowels /e/ and /ø/
543 biases the identification of the presented sound towards the percept /e/. We successfully
544 replicated this finding in normal-hearing individuals with the open-air presentation of auditory
545 stimuli. When we applied the same procedure to individuals with hearing impairment, we found
546 that the somatosensory effect in speech perception varied considerably and that these variations
547 could be related to their hearing thresholds in noise (with this evaluated in a separate test), and
548 to their hearing-impairment profiles. We categorized our participants with hearing impairment
549 into three groups. The first group consisted of participants who had a relatively lower hearing
550 threshold in noise and were able to auditorily identify the vowel sounds with reasonable
551 precision. It appears that this group did not show a consistent somatosensory effect. The second
552 group consisted of participants with a high hearing threshold in noise (≥ 0 dB SNR), who were
553 not able to auditorily identify the vowel sounds in the continuum. This group was further
554 divided into two subgroups based on the somatosensory effect displayed in the vowel
555 identification test. Participants in the first subgroup did not show any perceptual bias when the
556 somatosensory stimulation was applied. These were elderly participants who did not use a
557 hearing device before the age of 40 years or later, and had a relatively short duration of
558 experience with these devices (6 years at least, 21 years at most). Participants in the second
559 subgroup showed a large perceptual shift with somatosensory stimulation. Most of the
560 participants in this subgroup were pre-lingually deaf, were equipped with hearing devices very

561 early (≤ 3 years old for 6 over 8 participants) and had a long duration (> 18 years) of hearing
562 device usage. Members of this second subgroup also showed greater variability in production
563 while members of the other two subgroups showed a variability similar to NH participants.
564 Taken together, these findings indicate that the somatosensory effect in speech perception can
565 develop in individuals with hearing-impairment but that this development is highly dependent
566 on their hearing ability and history. We will now attempt to interpret how these three varied
567 portraits of somatosensory effect might have emerged in development, in relation with the
568 various hypotheses presented in the Introduction.

569 *Interpretations of the experimental behavior in the three groups*

570 The only participants found to display a large perceptual bias induced by the somatosensory
571 stimulation are those of the HI-2b group. The participants in this group were mostly prelingually
572 impaired and equipped early with a long duration of usage of their equipment which mostly
573 consisted of hearing aids with no or very reduced use of cochlear implants. Hearing aids simply
574 amplify the sounds coming to the ear while cochlear implants provide direct stimulation to the
575 auditory nerve after bypassing the damaged regions of the ear so it is likely that these
576 participants' auditory systems do not perform well, hence their high hearing thresholds in noise
577 and their poor vowel identification auditory performance. This also seems consistent with their
578 production performance showing that the produced formants varied more than in the other
579 groups. However, their long duration of usage of hearing aids (mostly from the prelingual age)
580 may still have habituated these participants to hear speech sounds in poor hearing conditions,
581 and led them to rely to a large extent on any available additional information. Interestingly, this
582 therefore shows that their production, even if imperfect, enabled them to capture the related
583 somatosensory cues and exploit them perceptually. Moreover, their poor audition is likely to
584 account for the large bias they displayed when experiencing the somatosensory stimulation
585 while listening to the speech sounds in the continuum. This pattern could be related to the

586 studies about audio-visual integration, mentioned in the Introduction, showing that, for
587 cochlear-implanted participants at least, early implantation (typically before 2.5 years of age)
588 is required to obtain efficient integration (Schorr et al., 2005). Six of the eight participants in
589 this group benefited from hearing aids at an early age (≤ 3 years) which is possibly compatible
590 with the 'critical period' that seems optimal for acquiring efficient multisensory integration
591 behavior (see also Kral & Sharma, 2012). Participants in this subgroup display a case of
592 'somatosensory dominance' that corresponds well to data on visual dominance in the McGurk
593 effect in cochlear-implanted individuals (Desai et al., 2008; Rouger et al., 2008; Schorr et al.,
594 2005). Interestingly, these participants display a unique situation that has never been explored
595 in previous studies in which it seems possible for them to recognize a vowel completely based
596 solely on the somatosensory input, since the auditory information essentially provides no valid
597 information in the categorization task for these subjects.

598 In this context, the results displayed by participants in the HI-1 group may appear puzzling.
599 Indeed, these participants were able to identify the vowels with some precision, but showed no
600 somatosensory effect. They had relatively low hearing threshold in noise, suggesting that their
601 auditory system was more efficient than in the other HI groups to some extent. Still, their
602 audition remained poorer than in the NH group if we consider both their hearing threshold and
603 identification curves that were often more blurred than in normal hearing participants, although
604 their variability of production was similar to that of NH participants. This could induce a lower
605 reliance on auditory information in this group than for the NH group. Based on principles of
606 sensory reliance claiming that interactions between different sensory systems are governed in
607 a statistically optimal way so that senses that relay better information contribute more to
608 perception (Alais & Burr, 2004; Ernst & Banks, 2002), we would predict a role of the
609 somatosensory stimulation at least as large in the HI-1 group as in the NH one. Still, the data
610 for this group are in line with the possible role of attentional processes in multisensory

611 integration, evoked in the Introduction. Indeed, it is likely that, even though their audition
612 performs rather well, the participants in this group might have to pay more attention in hearing
613 to achieve the proposed experimental task. We have supposed that the allocation of attentional
614 resources to the listening task might have reduced or totally blocked the somatosensory effect
615 in speech perception for this group. Interestingly, to our knowledge a decrease in multisensory
616 integration has never been reported in participants with hearing impairment for auditory-
617 lipreading fusion. Hence, it appears that auditory-somatosensory fusion could be more
618 dependent on attentional control. In our view, this matter would require further exploration in
619 future studies.

620 Finally, the participants in the HI-2a group were unable to identify the vowels correctly and
621 showed no somatosensory bias effect. This could be due to an age-related effect, since all the
622 participants in this group were over the age of fifty-five and received the hearing-aid devices
623 after the age for forty (see Figure 3b). This can also be exemplified by the variability of speech
624 production. While this small variability (comparable to that of NH participants and smaller than
625 that of the participants in HI-2b) suggests they had acquired normal speech production and
626 possibly an auditory-somatosensory interaction mechanism before their hearing loss, they later
627 lost both the ability to correctly identify the vowels and to let somatosensory processing interact
628 with the degraded auditory inputs. The decline of auditory-somatosensory interaction may be
629 in line with the decline of auditory-motor speech processing in aging adults with hearing
630 impairment (Panouillères & Möttönen, 2018). On the other hand, the data concerning audio-
631 visual integration in speech perception in older adults with hearing-impairment are
632 contradictory. Sometimes the data has been interpreted as showing that integration declines
633 with age (Musacchia et al., 2009; Tye-Murray et al., 2007), while others surmise that it actually
634 increases in seniors (Rosemann & Thiel, 2018; Sekiyama et al., 2014). Another interpretation
635 could be that a reduced and late experience with hearing-aid devices did not allow them to pay

636 sufficient attention to the somatosensory modality. In any case, the total absence of
637 somatosensory effect in this group with very poor audition shows that somatosensory cues are
638 much more fragile than their visual counterparts which an expected finding. To sum up, it
639 remains unclear how aging affects the somatosensory effect in aging individuals with normal-
640 hearing or hearing-impairment. Although we had the opportunity to test more older participants
641 with deafness and with hearing-aid devices, we stopped testing for the current exploratory
642 study, as the evaluation measures used in this study may not be sufficient to adequately interpret
643 the behavior of older adults with deafness. This limitation should be addressed in future studies
644 by including cognitive measures of some kind to assess the older adults' cognitive status, and
645 by including age-matched normal hearing participants in the control group.

646 The somatosensory effects in speech perception in participants with hearing impairment may
647 also be related to their speech production performance, extending our previous study which
648 showed that auditory-somatosensory integration was related to speech production performance
649 in NH individuals (Ashokumar et al., 2023). In the current study, we found that participants in
650 the HI-2b group, the only group to present clear – and strong – somatosensory effects, display
651 significantly larger variability than other HI or NH groups. This could also be in line with
652 previous findings that the accuracy of speech production can be related to the accuracy of
653 speech perception (Chao et al., 2019; Franken et al., 2017; Ghosh et al., 2010; Perkell et al.,
654 2004). The increased variability may be attributed to imprecise speech motor targets and hence
655 reflect less auditory ability in speech perception. Variability could be based on a limited number
656 of repetitions (six utterances) of each vowel and the current formant extraction might have led
657 to some misdetection but the larger variability in HI-2b cannot be due to these limitations since
658 participants in the other two HI groups (HI-1 and HI-2a) still showed a small but similar
659 variability to that found in the NH group. Accordingly, this difference in variability in
660 production is likely – and logically – to depend on hearing experience. The cause and

661 consequence in the present results remain to be determined, namely whether speech production
662 development in these participants affected the acquisition of auditory-somatosensory
663 integration for speech perception or the other way around.

664 *Limitations and proposals of future experiments*

665 While we tested variety of individuals with hearing impairment, unfortunately we could not
666 find adult participants who received cochlear implants before the above-mentioned critical
667 period which is probably because cochlear implants in infants were less popular twenty years
668 ago and more. Since prelingually deaf children using cochlear implants show better speech
669 perception and language development than those using conventional hearing aids (Bittencourt
670 et al., 2012), we can expect that individuals who receive cochlear implants before those critical
671 periods could develop real auditory-somatosensory integration associating efficient audition
672 and significant somatosensory bias.

673 Although the current somatosensory effect in the vowel identification task can be an effective
674 tool to investigate the somatosensory function and the production-perception link, the effect
675 can only be seen with ambiguous speech sounds, namely the sounds around the categorization
676 boundary in the normal-hearing participants. In addition, the amplitude of the observed effect
677 is relatively small, presumably due to the fact that speech perception is potentially mainly
678 auditory in nature. Participants with hearing impairment who have the hearing profile of HI-2b
679 could be good candidates to investigate this function further, considering the relatively large
680 somatosensory effect which is probably due to the fact that all presented speech stimuli can be
681 ambiguous for them.

682 Another limitation of the current study lies in the fact that we only tested one direction of skin
683 deformation because we primarily focused on examining whether participants with hearing
684 impairment show a similar somatosensory effect in speech perception, using a previously

685 examined auditory-somatosensory combination to do so. Testing other directions of skin stretch
686 stimulation in the participants with HI-2b hearing profile could provide further insights into the
687 somatosensory function in speech perception.

688 We initially predicted that the current somatosensory effect in speech perception could be
689 similarly induced in individuals with hearing impairment who received hearing devices and
690 sufficiently acquired speech production. One difference from our initial prediction was that
691 more than half of the participants did not show the target somatosensory effect in speech
692 perception. Nevertheless, the trends observed in each group have distinctive characteristics with
693 multiple factors of hearing profiles. Reporting all the results of an exploratory case study can
694 still be valuable for future research such as a follow-up investigation of the current
695 somatosensory effect but also for exploring other targets of interest, as it offers a new
696 perspective on the qualification of HI. Furthermore, as mentioned previously, the current
697 exploratory report suggested several new directions for such follow-up studies, namely: (1)
698 testing older individuals, including a battery of cognitive evaluations; (2) testing prelingually
699 deaf individuals who received CI before the prelingual period; and (3) testing the different
700 patterns of somatosensory stimulation in HI possessing the HI-2b hearing profile. In addition,
701 another important issue concerns testing children with deafness using hearing devices. Since
702 NH children have already been shown to display a somatosensory effect (Trudeau-Fisette et al
703 2019), it would be of great interest from a developmental perspective to find out whether
704 children with deafness present a somatosensory effect differently than adults with deafness with
705 the HI-1 hearing profile because of their immature speech production and perception abilities.
706 Alternatively, they may exhibit a similar effect to adults with deafness with the HI-2b profile
707 by perceiving all stimulus sounds as ambiguous because of their insufficient habituation to
708 hearing devices. Each of these potential studies should include a control group (age- and/or sex-
709 matched), thus ensuring a valid basis for comparison.

710 In summary, the present exploratory case study found that participants with hearing impairment
711 may present a somatosensory effect in speech perception but that this effect is highly variable
712 and appears not to be dependent on one single factor. Instead, it seems to derive from the
713 combination of multiple factors based on their hearing ability (represented by their hearing
714 threshold in noise) and hearing profile, and possibly related to speech production development.
715 Future studies should be devoted to find out more about the development and evolution along
716 life of the auditory-somatosensory integration in relation to hearing and speech production
717 abilities.

718

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722

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724 The authors declared no potential conflicts of interest with respect to the research, authorship,
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726

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732

733 **Data Availability Statement**

734 The datasets generated during and/or analyzed during the current study are available from the
735 corresponding author on reasonable request.

736

737

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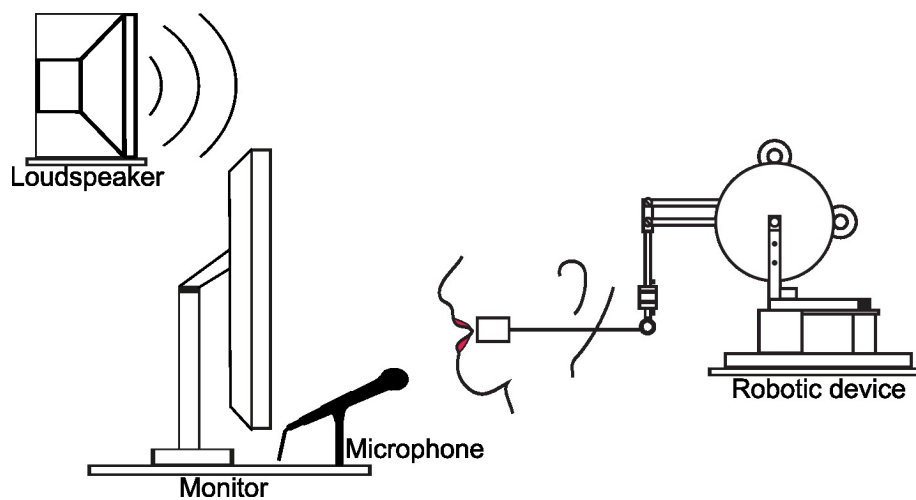


Figure 1. Experimental setup for the vowel identification test with somatosensory stimulation. This setup was also used in the speech-in-noise test by removing the tabs from the facial skin (no physical connection between the robotic devices and participants).

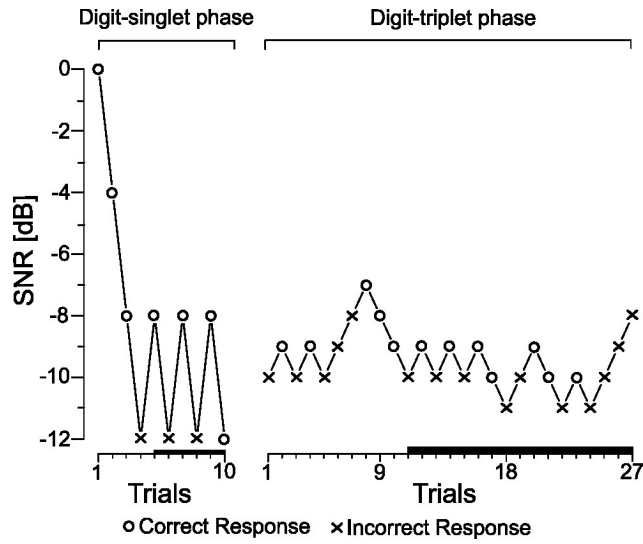


Figure 2. Representative example of participant's responses in the speech-in-noise test. The left panel represents digit-singlet phase (4 dB step change), and the right panel represents digit-triplet phase (1 dB step change). Circles represent correct responses and crosses represent incorrect responses. The black thick lines on the x-axis represent the trials used for calculating the average of the SNRs, respectively in the first and second phase of the test.

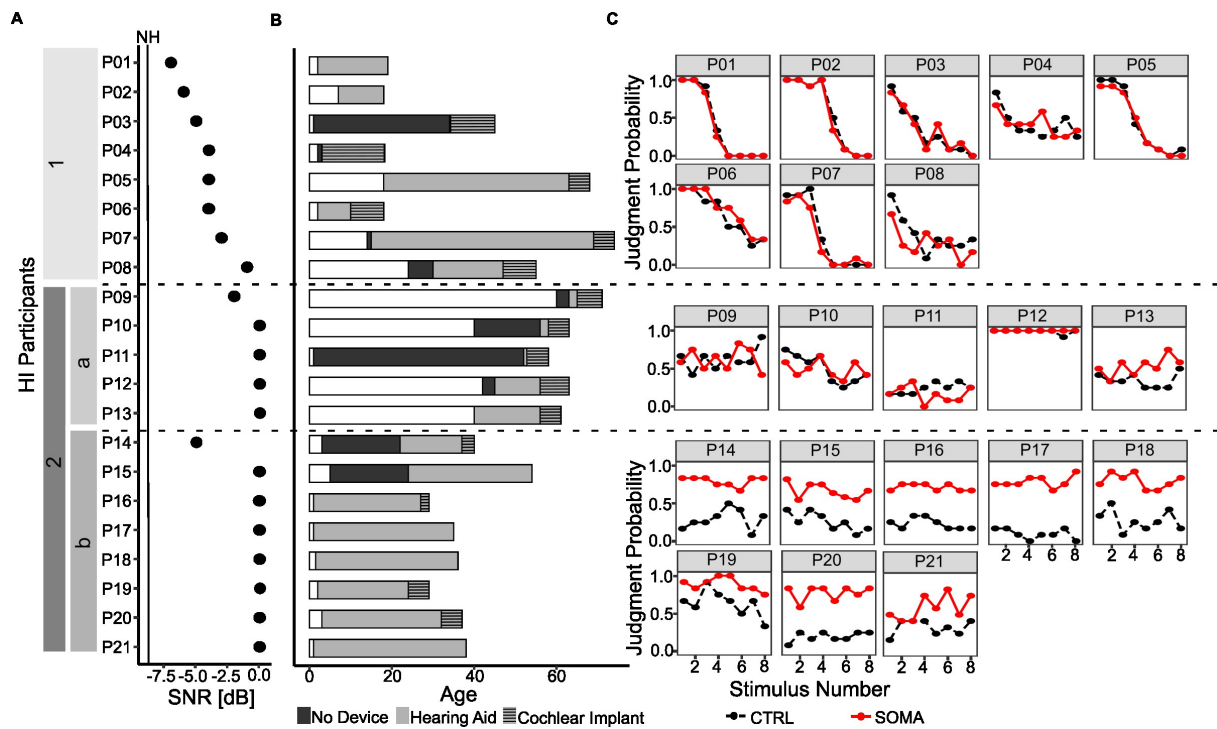


Figure 3. Results from the perception tests and hearing profile in each participant in HI. (A) Hearing thresholds obtained in the speech-in-noise test. The vertical line labeled NH represents the averaged threshold from normal-hearing individuals ($-8.5 \pm .1$ dB SNR). (B) Hearing profile across lifetime obtained by questionnaire. The entire length corresponds to the participant's age. White area represents the period before the detection of hearing impairment and filled area (black, light grey and striped gray parts) represents the duration after the detection of hearing impairment. In this filled area, the black part represents the duration of not using any hearing device, the light grey part represents the duration of using a hearing-aid, and the striped gray part represents the duration of using cochlear implants in either one or both ears. (C) Judgment probabilities in the vowel identification test. The red dots/lines represent the condition with somatosensory perturbation (SOMA). The black dots/lines represent the auditory-only condition (CTRL).

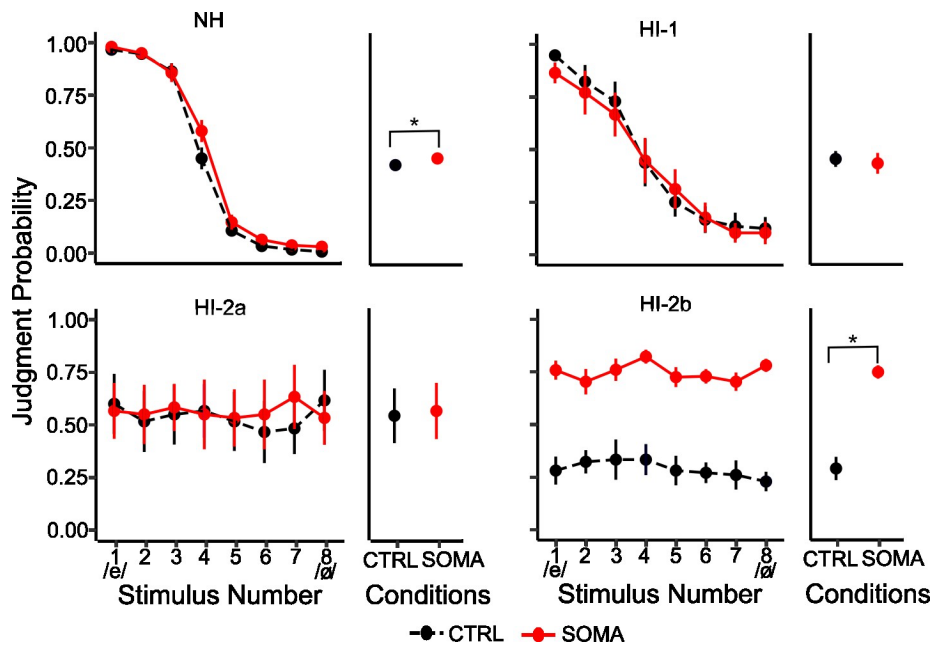


Figure 4. Averaged response of judgment probabilities in the vowel identification test. NH corresponds to the normal hearing group. HI-1, HI-2a and HI-2b correspond to the groups with hearing impairment represented in Figure 3. In each panel, the left part represents judgment probabilities across each auditory stimulus and the right part represents the judgment probabilities averaged across stimuli. Error bars represent standard errors across participants.

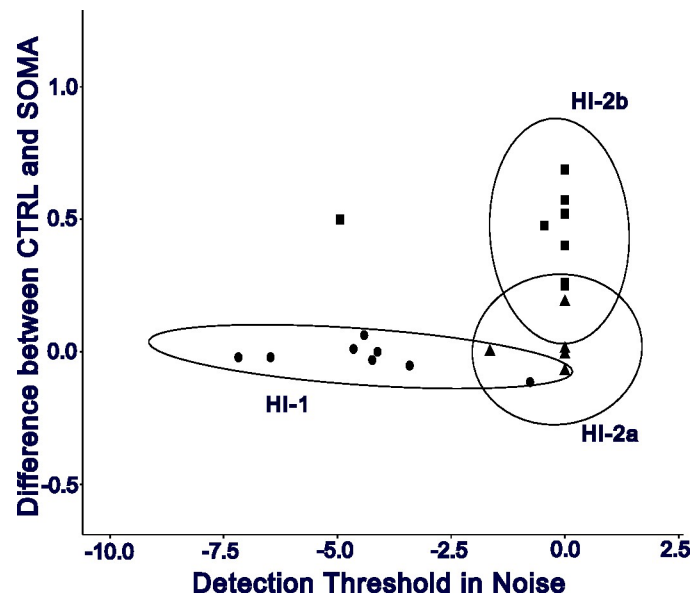


Figure 5. Relation between detection threshold in noise and amplitude of the somatosensory effect in the three HI groups (Black dots represent HI-1, triangles represent HI-2a and squares represent HI-2b; with dispersion ellipses (95% confidence intervals) for each group).

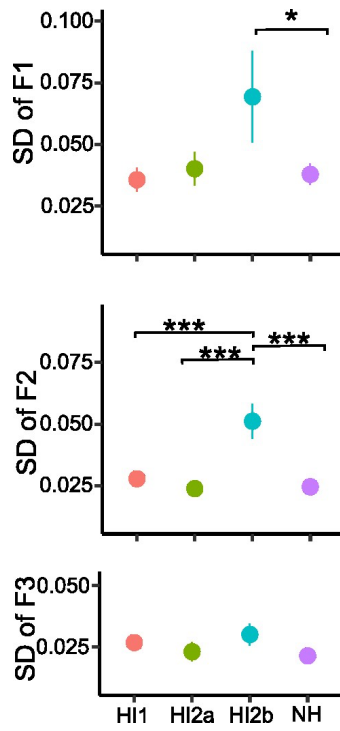


Figure 6. Mean of standard deviations for F1, F2 and F3 in the production task vowels in each group. Error bars show standard error across participants.