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Impact of visual and auditory deprivation on speech perception and production in adults

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ABSTRACT

Speech perception relies on auditory and visual cues and there are strong links between speech perception and production. We aimed to evaluate the role of auditory and visual modalities on speech perception and production in adults with impaired hearing or sight versus those with normal hearing and sight. We examined speech perception and production of three isolated vowels (/i/, /y/, /u/), which were selected based on their different auditory and visual perceptual saliencies, in 12 deaf adults who used one or two cochlear implants (CIs), 14 congenitally blind adults, and 16 adults with normal sight and hearing. The results showed that the deaf adults who used a CI had worse vowel identification and discrimination perception and they also produced vowels that were less typical or precise than other participants. They had different tongue positions in speech production, which possibly partly explains the poorer quality of their spoken vowels. Blind individuals had larger lip openings and smaller lip protrusions for the rounded vowel and unrounded vowels, compared to the other participants, but they still produced vowels that were similar to those produced by the adults with normal sight and hearing. In summary, the deaf adults, even though they used CIs, had greater difficulty in producing accurate vowel targets than the blind adults, whereas the blind adults were still able to produce accurate vowel targets, even though they used different articulatory strategies.

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Introduction

Background

Speech perception relies on auditory and visual cues. Whereas hearing is commonly needed to perceive speech, several studies have demonstrated that vision also plays a role (McGurk & MacDonald, 1976; Ménard, Cathiard, Troille, & Giroux, 2015; Ménard, Dupont, Baum, & Aubin, 2009; Sumby & Pollack, 1954; Summerfield, 1979). Authors have shown that visual information given by the upper part of the talker's face can be critical for intonation pattern perception (Lansing & McConkie, 1999). It is also well known that visible facial articulators such as the lips and the jaw help convey important aspects of speech, including information about the place of articulation (e.g., bilabial vs. non-bilabial sounds) and roundedness of consonants and vowels. Adding visual cues to auditory

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information helps normal-hearing individuals perceive speech more accurately, especially when there is background noise and acoustic quality is poor (Summerfield, 1992). In such cases, visual cues provided by visible facial articulators act as functional cues that supplement the auditory information transmitted by the speech signal. Several studies have shown that there are strong links between speech perception and production (Galantucci, Fowler, & Turvey, 2006; McGurk & MacDonald, 1976; Ménard et al., 2009). For example, the ability to distinguish between two spoken sounds may be related to the articulatory-acoustic contrast between the two sounds (Perkell et al., 2004). In the visual domain, a relatively recent review suggests that individuals who fail to acquire intelligible speech perform poorly in tasks that involve lip-reading (Woodhouse, Hickson, & Dodd, 2009).

The links between multisensory perception and production has been formalized within the Perception-for-Action-Control Theory of speech (PACT, Schwartz, Abry, Boë, & Cathiard, 2002; Schwartz, Basirat, Ménard, & Sato, 2012; Schwartz, Boë, & Abry, 2007). According to the PACT, speech goals are perceptuo-motor units, co-structured by perception and action. Sensory input provides the speaker with auditory, somatosensory and visual templates that guide speech gestures. Within that framework, individuals with sensory deprivation have access to impoverished input to build perceptuo-motor units.

Speech abilities in cochlear implant users

Individuals with severe-profound bilateral sensorineural hearing loss may be eligible for a cochlear implant (CI) that can partially restore hearing by converting auditory signals into electrical impulses. The device bypasses the missing or damaged hair cells in the cochlea and directly stimulates the neurons of the auditory nerve. Even after prolonged hearing loss, deaf individuals typically regain some functional hearing when using the device. Several studies have looked at speech perception abilities in CI users and they have reported different findings, depending on age at deafness onset, duration of deafness, number of years of implant use, residual hearing before surgery and communication modes (Hughes & Abbas, 2006; Peterson, Pisoni, & Miyamoto, 2010). With modern multi-electrode CIs, users can attain fairly high speech-performance scores for sentence recognition in a quiet environment, but speech perception can remain challenging for some users (Garnham, O'Driscoll, Ramsden, & Saeed, 2002; Osberger, Fisher, & Kalberer, 2000).

Several studies have described adaptive neural and compensatory behaviors in sensory-deprived individuals (for example, see Heimler, Weisz, & Collignon, 2014; Merabet & Pascual-Leone, 2010). The perceptual compensation hypothesis refers to the idea that sensory deprivation within one sensory modality will stimulate compensatory perceptual changes in another sensory modality (Ronnberg, 1995). In the case of early auditory deprivation, there is some debate over whether profound deafness results in visual deficits or an enhancement in visual performance (Dye & Bavelier, 2010). On one hand, some studies have documented improved visual processing in the peripheral visual field of deaf individuals. Compared with hearing individuals, they are faster and more accurate in detecting the direction of moving visual stimuli (Bosworth & Dobkins, 2002; Neville & Lawsom, 1987), they are better at detecting an increment in luminance (Loke & Song, 1991) and they have enhanced visual attention in the peripheral visual field (Bavelier et al., 2000); Bavelier & Dye (2006). On the other hand, other studies suggest that deafness leads to a deterioration of some visual functions. For example, higher visual temporal thresholds (Heming & Brown, 2005) and a reduced visual discrimination (Turgeon, Champoux, Lepore, & Ellemberg, 2012) have been reported in deaf individuals. Globally, research indicates that a lack of auditory stimulation early in life may lead to enhanced higher-level visual functions such as visual attention but also worse lower-level visual functions.

With respect to speech production, studies have demonstrated that deaf individuals who receive a CI show significant improvements in vocal and phonological development after implantation (Bouchard, Normand, & Cohen, 2007; Connor, Craig, Raudenbush, Heavner, & Zwolan, 2006; Serry & Blamey, 1999), including changes in formant frequencies (Lane & Webster, 1991; Ubrig et al., 2011), variation in vocal intensity, changes in resonance (Lejska, 2004), reduced dispersion of vowel formant values (Lane, Matthies, Perkell, Vick, & Zandipour, 2001; Vick et al., 2001) and increased vowel contrast in the formant space (Lane et al., 2005). Most of these studies used acoustic measures and perceptual judgments to examine changes in speech production. Another study used an objective method of speech intelligibility measure, a system computing word recognition. Participants were asked to read a standardized text and the system was computing words correctly pronounced. They were subdivided in three groups: prelingual deafness (group 1), postlingual deafness 2 years or less before implantation (group 2) or more than 2 years of deafness before implantation (group 3). They found that CI users with short duration of postlingual deafness (group 2) had a significantly better intelligibility compared to CI users with long duration of postlingual deafness (group 3) or with a prelingual deafness (group 1) (Ruff et al., 2017).

Few researchers, however, have examined objective articulatory measures in deaf individuals who used CIs. In a previous paper, we showed that tongue movements used to produce the vowel /u/ differed in CI users compared to individuals with normal hearing (Turgeon, Premont, Trudeau-Fisette, & Ménard, 2015). We examined 11 adults with normal hearing and 17 CI users (7 pre-lingually deaf and 10 post-lingually deaf adults). Short-term auditory feedback deprivation was induced by turning off the CI or by providing masking noise. Acoustic and articulatory measures were obtained during the production of /u/, with and without a tube inserted between the lips (perturbation) and with and without auditory feedback. In the absence of auditory feedback, pre-lingually deaf participants moved the tongue to a more forward position. We concluded that a lack of normal auditory experience of speech may affect the speaker's representation of a vowel. In a related study, we investigated speech production and intelligibility in 10 children with unilateral or bilateral CIs and 13 children with normal hearing. The participants produced multiple repetitions of five English vowels (/a/, /e/, /i/, /o/, /u/) with and without auditory feedback. Despite quite similar acoustic results, the two groups made different use of the tongue to implement vowel contrasts. The tongue position was lower in the feedback OFF condition than in the feedback ON condition for all participants, but the magnitude of this difference was larger for CI users than for their normal-hearing peers (Turgeon, Trudeau-Fisette, Fitzpatrick, & Ménard, 2017). Thus, the CI users displayed a larger difference than the normal-hearing participants between the feedback ON and feedback OFF conditions, suggesting that in the tongue height dimension, they had to rely more on auditory feedback to produce vowels and had not yet internalized robust feedforward commands.

Speech abilities in congenitally blind individuals

As is the case for auditory deprivation, several studies with congenitally blind individuals have also provided evidence of behavioral compensation and reorganization following sensory deprivation. An enhancement of certain aspects of hearing and an impairment of other tasks have been observed in visually impaired individuals. The enhanced performance seems to be related to the recruitment of occipital areas deprived of their normal visual inputs (Collignon, Voss, Lassonde, & Lepore, 2009; Gougoux, Zatorre, Lassonde, Voss, & Lepore, 2005). For example, early-blind individuals show superior auditory pitch discrimination (Gougoux et al., 2004) and they can map the auditory environment with superior accuracy (Lessard, Pare, Lepore, & Lassonde, 1998; Voss, Tabry, & Zatorre, 2015). On the other hand, neurophysiological studies support the hypothesis of auditory impairment in absence of vision, suggesting that vision can drive the maturation of certain auditory properties. For example, superior sound localization accuracy has been reported only for peripheral but not for central regions of space (Röder et al., 1999; Voss et al., 2004). Also, some aspects of localization tend to be worse in blind than in sighted controls (Amadeo, Campus, & Gori, 2019; Lewald, 2002).

In terms of speech perception, blind individuals display higher auditory processing skills in several tasks, including voice processing (Focker, Best, Holig, & Roder, 2012) and speech discrimination (Dietrich, Hertrich & Ackermann, 2013; Muchnik, Efrati, Nemeth, Malin, & Hildesheimer, 1991; Niemeyer & Starlinger, 1981). In the phonetic domain, Hirsch et al. (2011) report that, in a study of anticipatory coarticulation in French, blind individuals identified the rounded vowels earlier in a speech sequence than the sighted individuals. Along the same lines, Delvaux, Huet, Puccaluga, and Harmegnies (2018) show that blind listeners outperform their sighted peers in discrimination tasks, particularly in noisy conditions.

Although studies have shown that blind individuals have higher speech perception abilities, much less is known about the effect of visual deprivation on speech production. Several studies have reported delayed pragmatic, morphological and lexical development in blind children (for a review, see Pérez-Pereira & Conti-Ramsden, 1999). The production of gestures in blind toddlers is also reduced compared to their blind peers, suggesting that, although gestures are functional in communication early in life, their acquisition is also influenced by perceptual input (Iverson, Tencer, Lany, & Goldin-Meadow, 2000). Focusing more specifically on the speech domain, most of the studies have been conducted with children. Visual impairment deprives the child of an important source of information, which have consequences for the strategies used to produce phonological targets (Elstner, 1983). At the pre-babbling stage, Lewis (1975) reported less “imitation” of labial gestures by a blind baby compared to sighted babies. Blind babies also show longer babbling phases, as well as delays in the production of their first words (Burlingham, 1961; Warren, 1977). Elstner (1983) and Mills (1983, 1987) present various studies showing phonological delays and phonetic-phonological disorders in older blind children. As reported by Elstner (1983), it is difficult to study homogeneous populations of blind speakers because observed differences in speech production abilities between blind and sighted groups might equally well be related to the presence of uncontrolled variables, such as additional associated motor control disorders or language disorders unrelated to the visual impairment (also see Zeszut, 1998).

We have conducted a series of experiments to better understand the impact of blindness on speech production. For example, we demonstrated that sighted individuals produced significantly higher inter-vowel distances than blind speakers, presumably leading to better intelligibility (Ménard et al., 2009). In a follow-up study, we showed that visual deprivation influenced articulatory strategies used by blind individuals to produce French phonemes (Ménard et al., 2013). They used smaller differences in lip protrusion but larger differences in tongue position and shape compared to the sighted participants. These results suggest that vision regulates some of the phonetic implementation of phonological features and that congenitally blind speakers develop articulatory strategies based on nonvisual sensory templates and thus, compared with sighted speakers, they are less likely to associate visible lip gestures with nonvisual sensory templates. As a result, blind speakers seem to rely to a larger extent on auditory feedback to produce speech targets, suggesting sensory reorganization (Ménard, Trudeau-Fisette, Cote, & Turgeon, 2016).

According to the PACT (Schwartz et al., 2002; 2007; 2012), since speech goals are perceptuo-motor units, altered sensory input should have impact on motor actions involved in speech production. Although many studies have focused on a comparison between hearing adults and CI users, and, to a lesser extent, on sighted adults and blind individuals, none of them has compared the three speaker groups within the same single study. How do speech perception and production features observed in blind individuals compare with those observed in CI users? Examining individuals with auditory or visual deprivation could provide insights into compensatory mechanisms involved in speech production.

Objectives

We sought to better understand the influence of auditory and visual deprivation on speech perception and production by comparing spoken vowels produced by deaf adults who used CIs, blind adults, and adults with normal sight and hearing. We selected three vowels (/i/, /y/, /u/) based on their different auditory and visual perceptual salience. We aimed to, first, assess speakers' auditory discrimination and identification abilities through a speech perception task and, second, describe the articulatory displacement produced by the speakers to produce the target vowels. For the first time, the same vowels used for both a perception and a production task will be compared between blind and CI participants. This study will clearly demonstrate the deprivation consequences, either visual or auditory, without any confounding variables, on speech perception and production.

Methods

Participants

The study examined 12 deaf adults who used one or two CIs, who had a mean age of 41 ± 11.7 years (range, 27 to 67 years), 14 congenitally blind adults, who had a mean age of 43 ± 13.8 years (range, 25 to 63 years), and 16 adults with normal sight and hearing who had a mean age of 39 ± 9.7 years (range, 28 to 61 years). The CI users had severe, profound bilateral hearing loss before their CI surgery, and they used oral language as a primary mode of communication. With the device, they had sound detection thresholds above 40 dB HL (decibel hearing level) for all tested frequencies, which corresponds to what has generally been reported in the literature (Peterson et al., 2010). CI users also had perfect (20/20) vision or vision corrected by lenses, resulting in near-perfect vision. Table 1 presents the clinical characteristics of the CI users.

Table 1. Clinical profile of CI users.

Sex	Age	Etiology of deafness	Age at deafness (years)	Age at implantation (years)	Side of the Implant	Pre-implant hearing thresholds *(MPT)	Number of electrodes	Type of cochlear implant
F	35	Meningitis	3	8	R	>120/>120	9	Cochlear-Freedom
F	27	Unknown	8	10	R	>120/>120	6	Neurelec- Saphyr CX
F	41	Congenital	Birth	30	L	107/>120	16	Advances Bionic-Clarion
M	51	Congenital	Birth	1er:41, 2e: 49	Bil	95/93	14 Bil	Advances Bionic-Aida
M	50	Unknown	Birth	43	L	117/>117	20	Cochlear-Freedom
M	43	Hereditary	2	37	R	103/106	16	Advances Bionic-Clarion
F	29	Meningitis	2	22	L	110/91	22	Cochlear-Freedom
F	52	Unknown	10	1er:46, 2e: 52	Bil	118/107	16 Bil	Advances Bionic-Clarion
F	67	Hereditary	6	55	L	>105/>105	16	Advances Bionic-Clarion
F	44	Congenital	Birth	38	R	101/>120	22	Cochlear Freedom Nucleus
M	32	Congenital	Birth	1er:25. 2e; 32	Bil	107/107	24 Bil	Cochlear Freedom Nucleus
F	27	Congenital	Birth	16	R	>117/93	22	Cochlear-ESPrit 3G

*MPT = Mean of pure-tone (500, 1000, 2000 Hz). > no measurable response at the limit of the audiometer.

The blind participants had congenital, complete visual impairment, classified as class 3, 4, or 5 in the International Disease Classification of the World Health Organization (WHO). Table 2 presents their clinical characteristics.

The participants with normal sight and hearing (controls) had perfect (20/20) vision or vision corrected by lenses. The blind and control participants had auditory detection thresholds below 25 dB HL at every frequency, which corresponds to normal hearing. Pure-tone detection thresholds were assessed using an adaptive method at 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz with a supra-auricular earphone for the blind participants and the normal-hearing participants and in free-field for the CI users. Warble tones were used for all participants. All participants had Canadian French as their first language and reported having no motor deficits. None of the participants had a learning disability or other known medical conditions. All participants provided written, informed consent in accordance with the Board of Ethics of the University of Quebec in Montréal (UQAM).

Procedure

Perceptual task

The stimuli in the perceptual task consisted of three synthesized 5-formant vowels of French (/i/, /y/, /u/), which were selected based on their different auditory and visual perceptual saliencies. The articulatory features of these vowels are shown in Table 3. In traditional phonetics, for the / i / vs / y / pair, only the position of the lips varies (visible articulators) and the front position of the tongue (non-visible articulator) remains unchanged. Therefore, the vowels show similar F1 values but differ in terms of F2 and F3. For the /y/ vs/ u/ pair, only the position of the tongue varies (front for / y/ vs. back for /u/), while the position of the lips remains unchanged. This articulatory movement of the tongue causes an important variation of F2 values. Last, the / i / vs / u / pair has a more complex articulatory contrast where both the visible and non-visible articulators

Table 2. Clinical profile of blind participants.

Sex	Age	Etiology of blindness	Vision at birth	Current vision
M	25	Microphtalmie-congenital	total blindness	U[a] (total blindness)
F	32	Retinoblastoma-congenital	total blindness	U (total blindness)
M	23	Detachment of the retina- 1week	total blindness	U (total blindness)
M	27	Retinoblastoma-9 months	U	U (total blindness)
F	59	Microphtalmie-congenital	total blindness	U (total blindness)
M	52	Optic atrophy- congenital	U	U (total blindness)
F	60	Detachment of the retina	U	U (total blindness)
M	46	Detachment of the retina	U	U (total blindness)
M	50	Unknown	total blindness	R.E.[b] = 20/400 L.E.[c] = 20/400
F	50	Congenital cataract	U	R.E. = 0 L.E. = 6/1260
M	39	Unknown	U	U (total blindness)
M	63	Congenital cataract	total blindness	U (total blindness)
M	28	Leber's congenital amaurosis -congenital	U	U (total blindness)
M	45	Retinitis pigmentosa	total blindness	U (total blindness)

[a]Undetermined.
[b]Right eye.
[c]Left eye.

Table 3. Formant (F_i) and bandwith (B_i) values, in Hertz, of end-point stimuli/i/,/y/, and/u/synthesized for the perceptual experiment.

Vowel	F1	F2	F3	F4	F5	B1	B2	B3	B4	B5
/i/	236	2062	3372	3466	5000	78	13	61	154	154
/y/	236	1757	2062	3294	5000	88	40	19	19	19
/u/	236	705	2062	3294	5000	88	40	19	19	19

are involved (front tongue position and unrounded lips for /i/ vs. back tongue position and rounded lips for /u/), and these articulatory differences are reflected on F2 and F3 values.

For the perceptual test in the current study, the vowels were a subset of vowels that served as stimuli in a previous experiment (Ménard et al., 2009). They were created with the variable linear articulatory model (VLAM), using formant and bandwidth values presented in Table 4. All stimuli were 225 ms-long. Prior to the experiment, CI users were asked to adjust their implant processors to their usual settings.

To assess the auditory perception of the participants, two tasks were used: an identification task and a discrimination task. In the identification task, participants were asked to identify the three target vowels (/i/, /y/, /u/) that were presented twenty times each. Participants had to categorize 60 randomly presented tokens (French words) as a forced choice between 6 vowel options (/i/ as in "nid", /y/ as in "jus", /u/ as in "poux", /e/ as in "été", /o/ as in "auto" and /ø/ as in "nœud"). Table 4 summarizes features of height, place,

Table 4. Feature analysis for the 6 vowel choices provided to the listeners in the perceptual identification task.

	Feature		
Vowel	Height	Place	Roundedness
/i/	High	Front	Unrounded
/y/	High	Front	Rounded
/u/	High	Back	Rounded
/e/	Mid-high	Front	Unrounded
/ø/	Mid-high	Front	Rounded
/o/	Mid-high	Back	Rounded

and roundedness for the 6 vowels. These articulatory features were used later to determine error patterns. Vowels were presented spoken at a comfortable level of 70 dB SPL (decibel sound pressure level). This intensity was measured at the height of the listener's head. Participants indicated their responses by clicking on the vowel of their choice using a computer mouse. This task was especially important for the CI group, since it made it possible to account for their ability to successfully identify the vowels while wearing their CI. For the blind group, response options were clearly explained before the task. Blind participants had to tell their response to the experimenter, who selected the corresponding vowel on the computer screen.

In the discrimination task, participants were asked to discriminate between the three vocalic (vowel sequence) pairs through an AXB scheme. Each vowel sequence pair was assembled in its four possible forms. Thus, a total of 12 different vowel sequences were presented to the participants. Six repetitions of each pair were presented. As in the identification task, the experimenter selected the answer given by the blind participant. This task was conducted in order to compare auditory discrimination abilities between groups. Both perceptual tasks were performed using Praat (version 5.3.80) and took about 15 minutes in total.

Production task

In the production task, participants had to produce 20 repetitions of the fixed /i/, /y/, /u/ vowel sequence. Synchronous acoustic and articulatory recordings were conducted. Because the tongue is not visible, tongue displacement has been recorded by using invasive methods such as placing sensors in the mouth. However, ultrasound imaging provides the opportunity to evaluate articulatory strategies by measuring tongue shapes during a speech production task (Ménard, Aubin, Thibeault, & Richard, 2012). We thus made synchronous recordings of tongue movements in the midsagittal plane (at NTSC 29.97 Hz) and of the speech signal (at 44.1 kHz) using an ultrasound device (Sonosite 180 Plus) and a multidirectional microphone. A Northern Digital Optotrak system was used to concurrently record sounds and track the positions of infrared emitting diodes (IREDs) on the lips (at the vermilion border of the upper and lower lip) and chin. Four IREDs were also positioned on the ultrasound probe and three IREDs were placed on the forehead of participants, to provide a representation of the data in a movement-corrected head-centric frame of reference (HOCUS system, Haskins Optically Corrected Ultrasound system) (Whalen et al., 2005). The Optotrak sampling rate was 175 Hz. The experimental setup for the vowel production task is shown in Figure 1. After head-movement correction

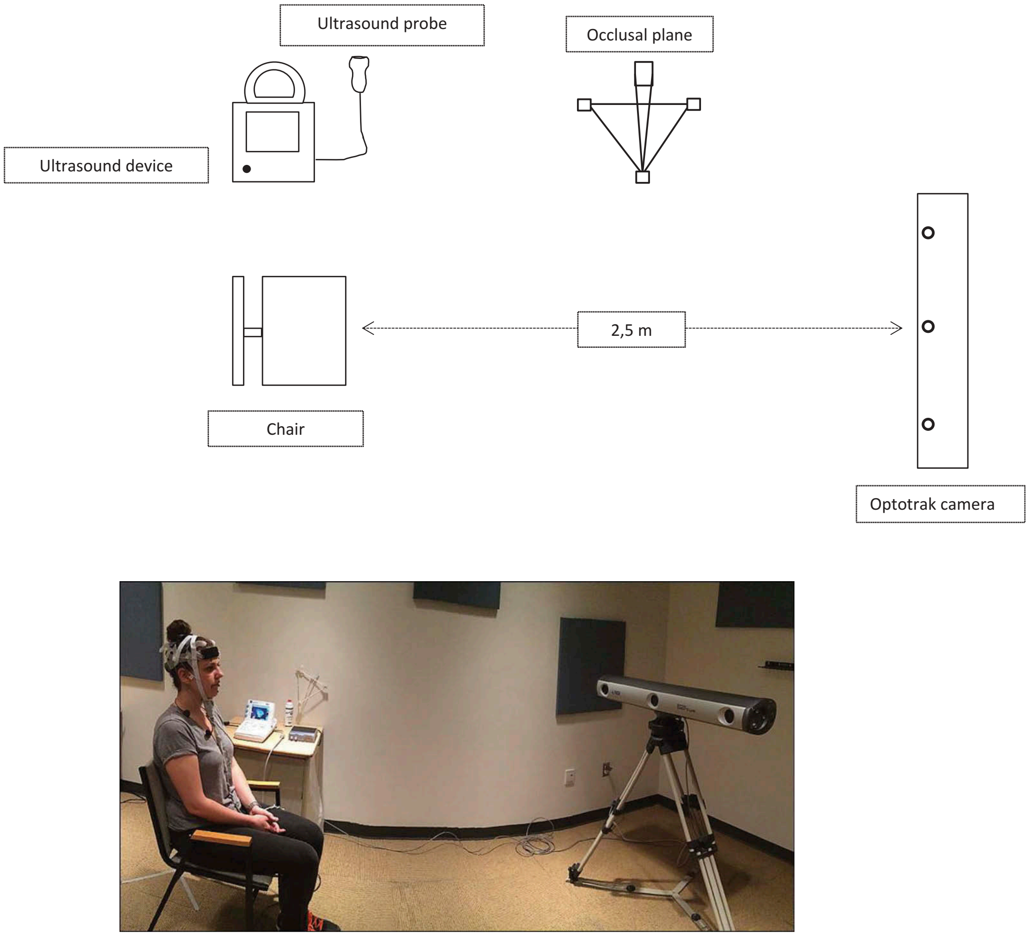

Figure 1. Experimental set-up.

and alignment to a coordinate system, the data were mapped onto a 3D view in which the position of the IREDs and the tongue imaging plane were visible.

Data collection

Perceptual task

For the identification and discrimination perceptual tasks, scores (% correct responses) were computed for each participant. Confusion matrices were built, and identification errors were compared across groups.

Production task

For the production task, acoustical data signals were digitized at a rate of 44,100 Hz. First and second formant frequencies (F1 and F2) were extracted at the vowel midpoints using a linear predictive coding (LPC) algorithm integrated in the Praat speech analyzer (Boersma & Weenink, 2014), which enabled an acoustic analysis at a time when formants were most stable. The features of place of articulation and rounding that distinguish the three vowels in this study can also be characterized according to their perceptual dimensions. To do so, it is common to transform the raw formant values (in Hertz) into Bark. We thus compared Bark values for F1, F2, using the following formula: (7*LN((values in Hz'/650)+√(1+((values in Hz/650)^2))). It has been previously shown that, when formant values were transformed into Bark, the difference between F2 and F1 values is significantly correlated with the perceived place of articulation (Ménard, Schwartz, Boe, Kandel, & Vallee, 2002). Indeed, F2-F1 values lower than 5 Bark indicate that a vowel is perceived in the posterior region of the oral cavity, whereas vowels with F2-F1 values higher than 5 Bark suggest that it is perceived in the anterior section of the oral cavity. The F2-F1 parameter was thus compared between groups.

To quantify the ability to contrast vowels and produce precise targets, we also evaluated the following two parameters that have been shown to be affected by sensory deprivation, (Lane et al., 2001; Ménard, Cote, & Trudeau-Fisette, 2016; Ménard et al., 2009, 2016; Turgeon et al., 2017): (1) the contrast between vowels (where reduced contrast generally correlates with diminished intelligibility) and (2) the dispersion within a vowel (which is a measure of accurateness of vowel production, where the smaller the dispersion, the more accurate the production). Measures of between-category contrast distances were obtained by computing the Euclidean distances, using Bark values, between the three possible vowel pairs /i/ vs /u/, /i/ vs /y/, and /y/ vs /u/. This measure has previously been used several times in clinical populations. To measure within-category dispersion, we determined, for each repetition of each vowel, the Euclidian distance of that single token in the F1 X F2 plane from the average position of all the repetitions of those vowels.

Articulatory data – tongue shape and position

Tongue images at vowel midpoint were imported using Adobe Premiere Pro. Tongue contours were extracted using a semi-automatic detection method described by Li et al (Li, Kambhamettu, & Stone, 2005). The resulting 100-point sagittal tongue contours were exported to an internally developed Matlab application, Lingua, which extracts several parameters that quantify tongue contours Figure 2, from Ménard, Aubin, Thibeault, and Richard (2012), shows the different parameters that allow the characterization of the articulatory movement of the tongue: the tongue position (*x-y* coordinates of the highest point of the tongue) and the tongue shape (tongue curvature). Regarding the tongue position, the *x-y* coordinates of the highest point of the tongue (C) represent tongue height (*y*) and front-back position (*x*). Regarding tongue shape, various metrics have been used in previous studies to measure tongue shape (see, for instance, Gick and Stolar (2013) or Dawson, Tiede, and Whalen (2016)). Although those metrics are very relevant as they do not rely on observed tongue tip and root on the ultrasound image, we used the curvature degree defined in Ménard et al. (2012) since this index has proven useful to compare tongue shapes in high vowels such as /u/ in French speakers (see for instance, Ménard, Leclerc, and Tiede (2014)). Tongue curvature degree is defined as the ratio of the distance AB (which refers to the distance between de root and the tip of the tongue) over the distance CD (referring to the height of the triangle on the AB base). So, as the tongue curvature diminishes, the tongue is more bunched, whereas when the curvature is high, the tongue is flatter (Ménard et al., 2012). Those parameters were previously shown to be useful to distinguish between the vowels, as in the current study (Ménard et al., 2012).

Figure 2 shows two different tongue shapes, where root to tip midsagittal contours of the tongue are given by x, y coordinates, and triangles are used to describe curvature. The

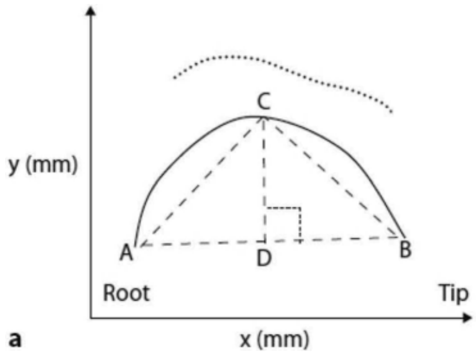

Figure 2. Tongue position (*x-y* coordinates of the highest point of the tongue) and the tongue shape (tongue curvature).

solid line represents the tongue contour and the dashed lines represent a triangle that fits the contour. Tongue front-back position corresponds to point C. Tongue curvature corresponds to the ratio AB/CD, where AB = distance between the root and the tip of the tongue, and CD = height of the triangle on the AB base.

Articulatory data – lip geometry

The acoustic onsets and offsets of the target vowel were labelled on the acoustic signal, and the IRED coordinates were extracted at the vowel midpoints. Three parameters were used to characterize lip geometry: lip opening (distance, in the vertical dimension, between the upper lip IRED and the lower lip IRED), lip protrusion (distance, in the horizontal dimension, between the upper lip IRED of both vowel /y/ and /u/ and the one of the reference position (vowel /i/), and lip stretching (distance, in the lateral dimension between the two IREDs placed on the mouth commissures).

Statistical analyses

Perceptual tasks

Linear mixed-effects models were built for each dependent variable (discrimination scores and identification scores) using the *lme4* (Bates, Maechler, Bolker, & Walker, 2012) package implemented in R (R Core Team, 2012). The fixed effects were the speaker group (control, blind, and CI groups) and the vowel (/i/, /y/, /u/), and the intercepts for participants were considered as a random effect. Visual inspection of residual plots was used to confirm the absence of any obvious deviation from homoscedasticity or normality. In the absence of deviation, the statistical analyses were considered to be valid and *p*-values were obtained by likelihood ratio tests of the full model with the effect in question versus the model without the effect in question. Results for which *p*-levels were below 0.05 were considered significant. In cases where the response did not correspond to the produced vowel, the produced and perceived vowels were compared according to the articulatory features presented in Table 4. Errors were grouped into three categories: height, place, or roundedness. Height errors were those for which the height of the perceived vowel did not correspond to the height of the stimulus regardless of the other features (for instance /i/ perceived as /e/ or /ø/ or /o/). Place errors corresponded to cases were the perceived place of articulation did not correspond to the stimulus' place of articulation, regardless of other features (for instance /y/perceived as /o/). Roundedness errors corresponded to cases where the perceived value of rounding did not correspond to the stimulus' rounding value regardless of other features (for instance /i/ perceived as /ø/). A linear mixed-effects model was also built with the number of errors as the dependent variable. The group and feature were included as fixed effects, and the intercepts for participants were considered as a random effect.

Production tasks-acoustic data

Three separate linear mixed-effects models were first computed on F1, F2, and F2-F1 (in Bark values) at the vowel midpoint as the dependent variable. Group (control, blind, or CI groups) and vowel (/i/, /y/, /u/) were the fixed effects, and the intercepts for participants were included as random effect. Another linear mixed-effects model was built with dispersion values (averaged across F1 and F2 in Bark) as the dependent variable, group and vowel as the fixed effects and participants as the random effect. Finally, contrast values (in Bark) between /i/-/u/, /i/-/y/ and /y/-/u/ were used to compute another linear mixed-effects model including group and contrast as the fixed effects and participants as the random effect.

Articulatory data – tongue shape and position

Three separate linear mixed-effects models were built with (1) tongue height (y-coordinates of the highest point of the tongue), (2) tongue position (x- coordinates of the highest point of the tongue), and (3) tongue shape (curvature) as the dependent variables. The fixed effects were speaker group (control, blind, and CI group), and vowel (/i/, /y/, /u/), and the intercept for participants was the random effect.

Articulatory data – lip geometry

Two separate linar mixed-effects models were computed on lip geometry with lip opening (distance, in the vertical dimension, between the upper lip IRED and the lower lip IRED) and lip protrusion (distance, in the horizontal dimension, between the upper lip IRED and the reference position- /i/) as the dependent variables, group (control, blind, or CI group), and vowel (/i/, /y/, /u/) as the fixed effect and participant (intercepts) as the random effect.

Results

Perceptual tasks

Results of the perceptual tasks are presented in Figure 3. The linear mixed-effects model performed on identification scores revealed a main effect of group ($\chi^2(6) = 49.85$; $p < .001$), with CI participants having worse results than control or blind participants (who had near perfect scores). No significant differences were observed between normal-hearing and blind participants. The linear mixed-effects model built with discrimination scores also revealed a main effect of group ($\chi^2(24) = 71.95$; $p < .001$). CI participants again had worse results than control or blind participants. No significant difference was observed between normal-hearing and blind participants.

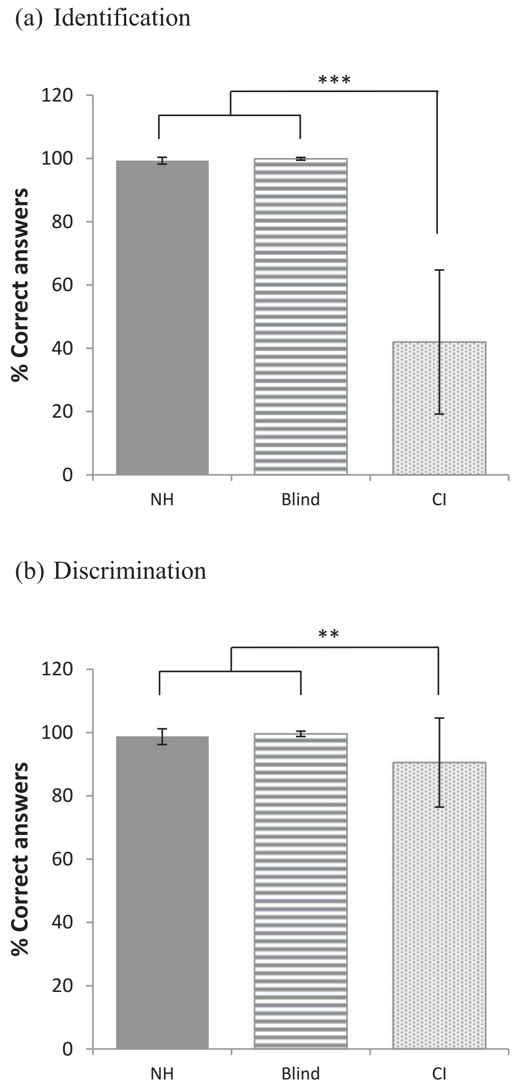

Figure 3. Identification and discrimination scores for normal hearing adults (NH), blind adults and cochlear implants users (CI).

Table 5 provides confusion matrices for each vowel stimulus and shows the type of perceptual errors made in the three groups of participants. Although there were very few errors in the normal-hearing and blind-participant groups, it is worth noting that blind participants only made errors with the vowel /i/, which they perceived as /y/ 0.4% of the time. Normal-hearing participants produced errors that were mainly associated with height, where the high vowels /i/, /y/, and /u/ were perceived as their more open (mid-high) counterparts /e/ (2.7%), /ø/ (3.7%), and /o/ (5.3%). CI users made several errors.

Linear mixed-effects models built on the perception errors associated with the CI participants with the percent error as the dependent variable and the stimulus (/i/, /y/, /u/) and feature (height, place, rounding) as the fixed effects revealed a significant effect of feature on

Table 5. Confusion matrices for the vowel stimuli, in the three participant groups.

Produced ↓	/i/	/y/	/u/	/e/	/ø/	/o/
			Normal hearing: Perceived			
/i/	**96.0**	1.0	0.3	2.7	0.0	0.0
/y/	0.0	**96.3**	0.0	0.0	3.7	0.0
/u/	0.0	0.7	**94.0**	0.0	0.0	5.3
			Blind: Perceived			
/i/	**99.6**	0.4	0.0	0.0	0.0	0.0
/y/	0.0	**100.0**	0.0	0.0	0.0	0.0
/u/	0.0	0.0	**100.0**	0.0	0.0	0.0
			CI: Perceived			
/i/	**40.8**	14.2	2.1	35.8	6.3	0.8
/y/	4.6	**43.8**	1.3	10.8	38.3	1.3
/u/	3.3	2.9	**53.8**	0.4	4.2	35.4

The table shows responses for normal-hearing adults, blind adults, and cochlear implant users (in percent). The percent of correctly perceived responses are bolded.

the identification errors ($\chi^2(6) = 144.56$; $p < .001$). The percent errors in the height dimension were significantly higher than the other types of errors ($p < .001$) and the percent errors in the rounding dimension were significantly higher than those in the place dimension ($p < .001$).

Acoustic data

Figure 4 presents average F1 values for the three vowels and the three participant groups. The linear mixed-effects model revealed a significant interaction between group and vowel $\chi^2(4) = 54.61$; $p < .01$. Normal-hearing and blind participants had lower F1 values than CI users for /i/ and /y/. For /u/, on the other hand, F1 values did not differ across speaker groups. There was a significant main effect of group $\chi^2(2) = 17.06$; $p < .05$, with CI users having overall higher F1 values.

Figure 5 presents average F2 values. As suggested by this figure, a significant interaction was found between vowel and group $\chi^2(4) = 69.10$; $p < .01$. CI users had lower F2 values

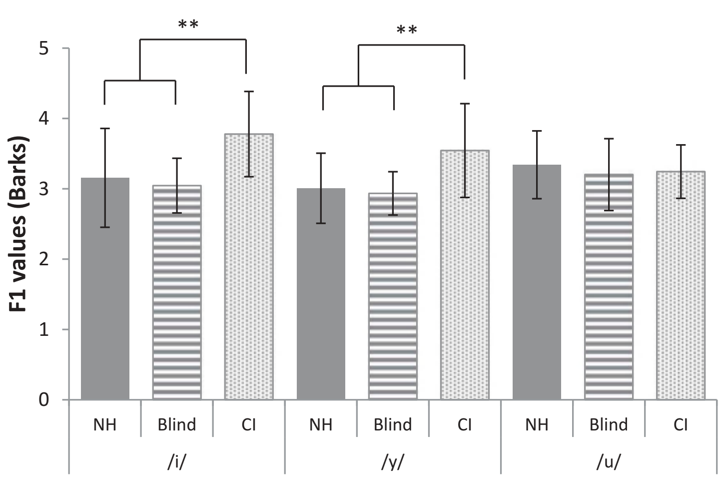

Figure 4. F1 values for vowels/i/,/u/and/y/for normal hearing adults (NH), blind adults and cochlear implants users (CI).

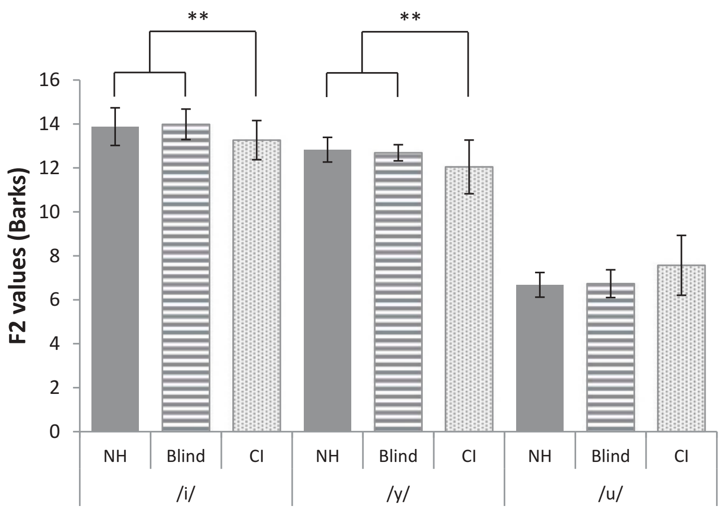

Figure 5. F2 values for vowels/i/,/u/and/y/for normal hearing adults (NH), blind adults and cochlear implants users (CI).

than normal-hearing and blind participants for the vowels /i/ and /y/. No main effect of group was found. As expected, a main effect of vowel was found, $\chi^2(2) = 144.38$; $p < .001$, since /u/ is known to have lower F2 values than /i/ or /y/ (more posterior).

As suggested by Figure 6, a main effect of vowel was found for the values of F2-F1 (in barks), $\chi^2(2) = 137.26$; $p < .001$ with /u/ resulting in smaller F2-F1 values than /i/ and /y/. These results were expected, since the front vowels (/i/ and /y/) should have F2 and F1 values that are spaced further apart resulting in larger F2-F1 values. In contrast, the back vowel /u/ should have F2 and F1 values that are close to each other, resulting in smaller F2-F1 values. A significant interaction between vowel and group was also found $\chi^2(4) = 73.98$; $p < .01$.

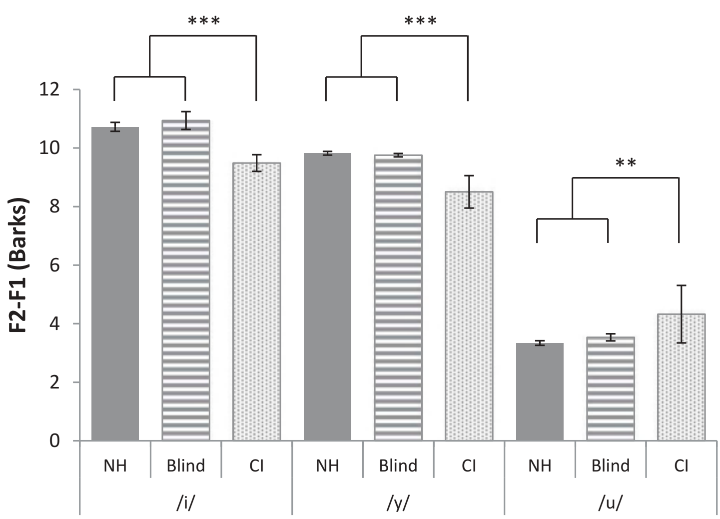

Figure 6. Difference between F2 and F1 values for vowels/i/,/u/and/y/for normal hearing adults (NH), blind adults and cochlear implants users (CI).

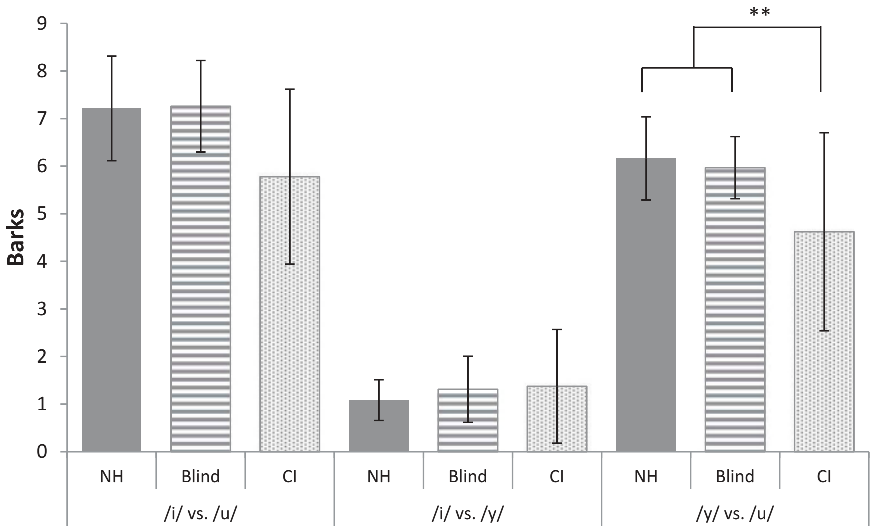

Figure 7. Contrast values between vowels/i/,/u/and/y/for normal hearing adults (NH), blind adults and cochlear implants users (CI).

Compared to the two other groups, CI users presented smaller F2-F1 values for /i/ and /y/ and larger F2-F1 values for /u/. Our results suggest that CI users produced less typical vowels than control and blind participants. A main effect of group was obtained, $\chi^2(2) = 32.47$; $p < .01$, with CI having overall lower F2-F1 values.

As suggested by Figure 7, the linear mixed effects models computed on contrast values revealed a significant interaction between vowel and group $\chi^2(4) = 20.85$; $p < .05$. CI users presented lower contrast for the /y/-/u/ pair compared to the other groups. No significant difference was obtained between groups for the /i/-/y/. A main effect of group was also obtained $\chi^2(2) = 32.07$; $p < .01$, with lower values for CI users. Lower contrast in CI users suggests that their speech targets are not as spread out as those of blind and control speakers, which can lead to poorer intelligibility. As expected, we obtained a main effect of vowel $\chi^2(2) = 175.39$; $p < .001$. We obtained a larger contrast between /i/-/u/ and /y/-/u/ compare to /i/-/y/.

The average dispersion values are depicted in Figure 8. The results revealed a significant interaction between group and vowel $\chi^2(4) = 41.04$; $p < .05$. There were higher dispersion values for the CI users for the vowels /i/ and /y/. This means that CI users are not as constant as the two other groups in their speech pronunciation over multiple repetitions, especially for those vowels. Higher dispersion values can be associated with lower intelligibility. A main effect of group was obtained $\chi^2(2) = 14.69$; $p < .05$, with overall higher values for CI users. Significant differences were found between normal-hearing and CI users ($p < .01$) and between blind participants and CI users ($p < .01$). There was also a main effect of vowel $\chi^2(2) = 69.52$; $p < .01$, with higher values for /u/, then /i/ and /y/ (p < .01).

Articulatory data – tongue shape and position

As mentioned earlier, tongue height is defined as the y-coordinates of the highest point of the tongue (as shown in Figure 2). The linear mixed effects model computed with tongue

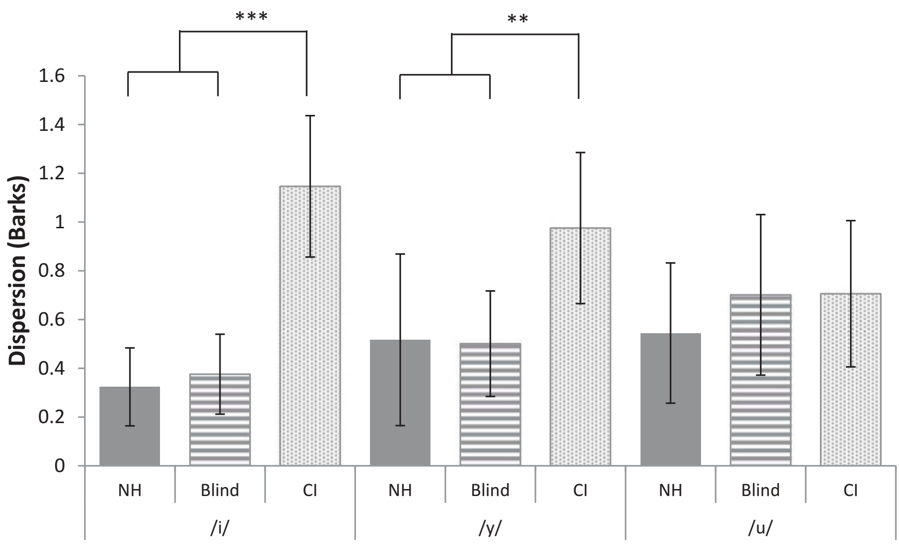

Figure 8. Dispersion ellipses in the F1 and F2 values for vowels/i/,/u/and/y/for normal hearing adults (NH), blind adults and cochlear implants users (CI).

height revealed no significant difference according to speaker group or vowel. This was expected since the three target vowels are all high vowels, involving a high tongue position.

As was also mentioned earlier, tongue front-back position is defined as the x- coordinates of the highest point of the tongue (as shown in Figure 2). As suggested by Figure 9,

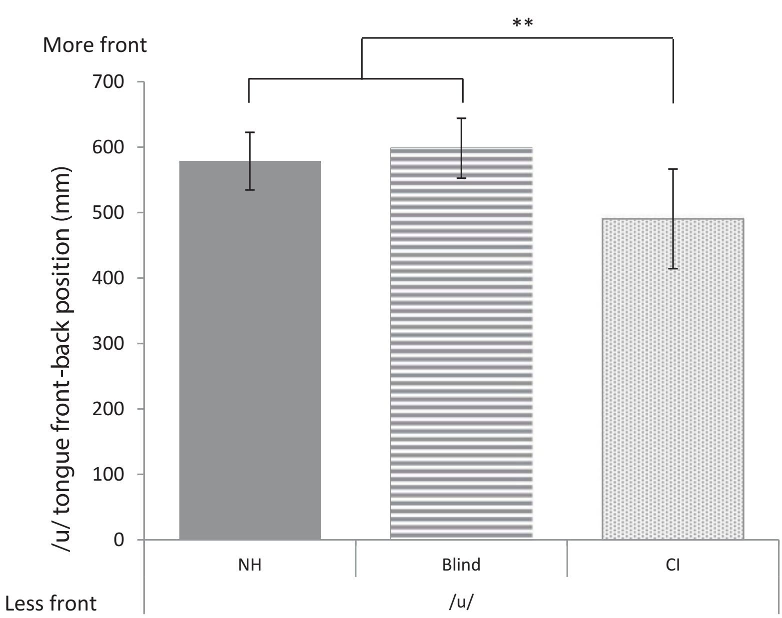

Figure 9. Tongue front-back position for vowel/u/for normal hearing adults (NH), blind adults and cochlear implants users (CI).

a significant interaction between vowels and groups was found $\chi^2(4) = 57.12$; $p < .01$. CI users produced the vowel /u/ with a tongue position that was more anterior than that of normal-hearing or blind participants, which is a less typical place of articulation for this back vowel. No main effect of group was found. As expected, a main effect of vowel was found, $\chi^2(2) = 148.39$; $p < .01$, since /u/ is known to be produced with a more back tongue position than /i/ and /y/ (which are more anterior).

As the tongue curvature diminishes, the tongue is more bunched, whereas when the curvature value is high, the tongue is flatter (as shown in Figure 2). As suggested by Figure 10, tongue curvature did not vary significantly according to group but a significant difference according to vowel was found $\chi^2(2) = 58.25$; $p < .01$. As expected, since /u/ is the vowel for which tongue shape is typically more bunched, we obtained lower curvature values for /u/.

Articulatory data – lip geometry

Lip opening was defined as the distance in the vertical dimension between the upper lip IRED and the lower lip IRED. As suggested by Figure 11, the vowel and group factors had a significant interaction effect on lip opening $\chi^2(4) = 48.11$; $p < .01$. Blind participants had higher lip opening values than participants with normal sight and hearing or CI users for the vowel /i/. Since all three target vowels are commonly characterized as closed vowels, they should all be associated with a small lip opening value. In this study, blind speakers had lip-opening values for /i/ that were not typical. No main effect of group and vowel was found.

Lip protrusion was defined as the distance in the horizontal dimension between the upper-lip IRED and the reference position (the position for /i/ since it is pronounced without any protrusion). As suggested by Figure 12, lip protrusion for /u/ and /y/

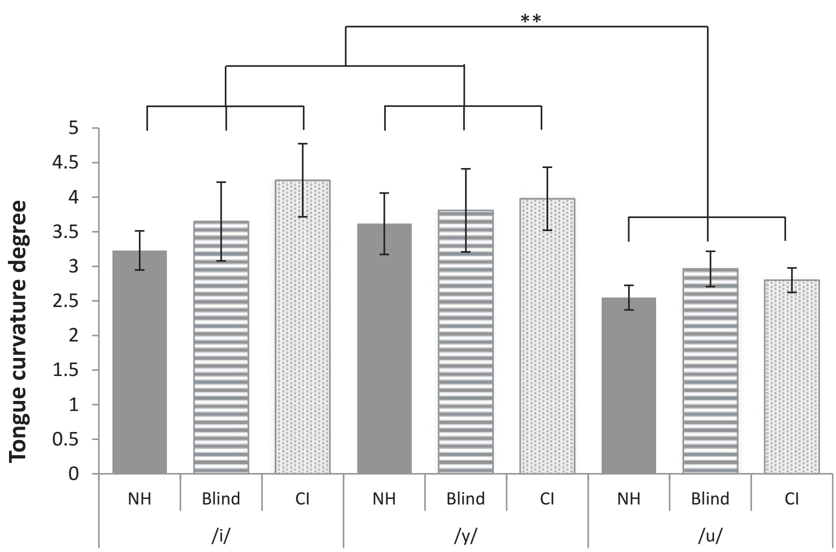

Figure 10. Tongue curvature values for vowels/i/,/u/and/y/for normal hearing adults (NH), blind adults and cochlear implants users (CI).

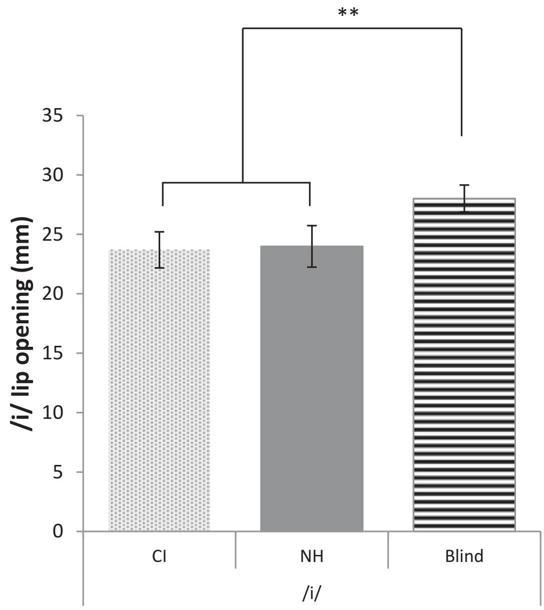

Figure 11. Lip opening for vowel/i/for normal hearing adults (NH), blind adults and cochlear implants users (CI).

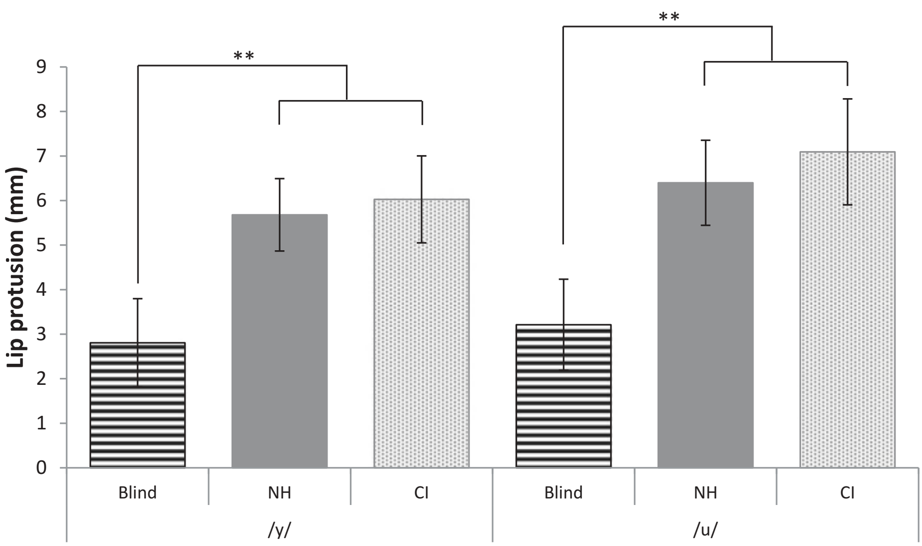

Figure 12. Lip protrusion for vowels/u/and/y/for normal hearing adults (NH), blind adults and cochlear implants users (CI).

significantly varied according to group $\chi^2(2) = 42.68$; $p < .01$. Post-hoc analyses revealed that blind participants had smaller lip-protrusion values than normal-hearing participants ($p < .05$) and CI users ($p < .05$). This suggests that, as a result of their visual deprivation, blind speakers were less able to use their lips (visible articulators) to successfully produce those rounded vowels. There was no significant difference between participants with normal sight and CI users. There was also a main effect of vowels $\chi^2(1) = 12.79$; $p < .01$, with /u/ having a larger lip protrusion value compared to /y/, which was expected.

Discussion

Perceptual tasks

The CI users in this study were less able than other participants to identify and discriminate between the vowels /i/, /y/ and /u/. Even though hearing is partly restored by the CI device, the CI users had worse scores than normal-hearing individuals (who mostly had perfect scores). The studied vowels /i/, /y/ and /u/ have relatively similar F1 values, but different F2 values. CI devices might not be precise enough to allow users to identify this auditory perceptual difference without visual cues. No between-group difference for speech identification or discrimination was found between blind and normal-hearting participants. Previous studies have shown group difference between blind and normal-hearing individuals for a speech discrimination task with competing noise (Niemeyer & Starlinger, 1981). The absence of a group difference between blind and normal-hearing individuals for the speech discrimination task in the current study may reflect a ceiling effect. On the other hand, the current results are consistent with results of our earlier study (Ménard et al., 2009), where higher discrimination scores in blind participants were found for /e/-/ɛ/ and /ɛ/-/a/, but not for /i/-/y/.

CI users made more errors of vowel rounding and height than place of articulation. Since vowel rounding and height are mainly implemented by movements of the lips and jaw (visible articulators) whereas place of articulation involves tongue position, it is likely that for vowel rounding and height, CI users likely put more weight on visible articulators than on acoustic patterns. These results are in line with a previous study showing that visual cues for vowel lip rounding are generally used more heavily by listeners with a CI compared to control participants (Winn, Rhone, Chatterjee, & Idsardi, 2013).

Acoustic data

Overall, the acoustic results suggest that CI users produced vowels that are less typical and less precise than their control and blind peers. Contrast distances between the three vowels were smaller in CI users than in the other groups. There was no significant difference in contrast distance in the normal-hearing participants and blind individuals. Lower contrast in CI users suggests that their speech targets were not as spread out as those of blind and control speakers, which could lead to poorer intelligibility. These results were not surprising. In previous studies with adult CI, we also obtained atypical acoustical values for vowels. In one study, our group investigated the effects of speaking condition (ex: regular vs fast speech) and auditory feedback (implant turn ON and OFF) on vowel production by post lingually deafened adults (Ménar et al., 2007). Another study used short-term auditory feedback deprivation by turning ON or OFF the implant on pre and post lingually deafened adults (Turgeon et al., 2015). Other studies have also shown that CI users can present with atypical abilities for certain aspects of speech, such as control of the orofacial articulators and intelligibility (Habib, Waltzman, Tajudeen, & Svirsky, 2010).

However, in earlier work we showed that when cochlear implantation occurs early in life, the overall intelligibility of the CI users can be comparable to that of their normal-hearing peers (Turgeon et al., 2017). In that study, CI users were a heterogeneous group. They became deaf between birth and age 10, underwent CI surgery when they were 8 to 55 years old, and had different progression of hearing loss. Since speech production quality is related to the onset and duration of deafness, (Ruff et al., 2017), the variability between subjects in that study may explain why some CI users had poorer contrast values. The perceptual results in the current study agree with the acoustical results in the earlier study. It has also been shown that poorer perceptual abilities can lead to smaller produced contrast between vowel targets (Perkell et al., 2004). If, as suggested by the speech perception results in the current study, CI users have less defined vowel targets, it is not surprising that they produced vowels that are less segregated in the acoustical space.

Regarding the auditory-perceptual parameter F2-F1, it is worth noting that in our data, CI users presented F2-F1 values that were atypically elevated for the vowel /u/. Thus, despite auditory restoration provided by the CI device, speakers had not reached a level of speech production accuracy typical of normal-hearing participants.

It has been suggested that because babies establish relationships between auditory and visual information during early language acquisition, visual impairment deprives a child of an important source of information when learning to speak. Blindness can affect the strategies children develop to produce phonological targets. For example, we conducted acoustic analyses of the ten isolated French vowels (/i y u e ø o ɛ œ ɔ a/), and we demonstrated that sighted individuals produced significantly higher inter-vowel distances than blind speakers (Ménard et al., 2014). Another study in blind adults reported similar results (Ménard et al., 2009).

Other studies, however, have reported that even though blind individuals tend to use different articulators to produce speech sounds, they can produce acoustic patterns that are comparable to those of sighted speakers. For example, Trudeau-Fisette et al. reported that in blind and sighted speakers, there was no difference in F1 and F2 for the French vowels /i y u a/ even though the two groups used different articulatory strategies (Trudeau-Fisette, Turgeon, & Côté, 2013). In the current study, we found no significant differences in speech production between blind participants, controls with normal sight and hearing, and CI users. However, we studied vowels uttered in isolation, so they were not influenced by the preceding or following sounds, whereas Trudeau-Fisette et al (Trudeau-Fisette et al., 2013) examined vowels uttered in a carrier phrase. Furthermore, they used electromagnetic articulography (a fleshpoint tracking method) to measure articulatory displacement, whereas we used a technique combining an ultrasound device and an IRED motion capture system. Those differences in method likely explain differences in the findings.

Articulatory data

CI users produced the vowel /u/ with a tongue position more anterior than that of control or blind participants. This position is a less typical place of articulation for this back vowel. We reported similar findings in a previous study in which we explored the perception-production relationship in normal-hearing and CI users through a lip-tube paradigm. When trying to compensate for the lip opening caused by the lip-tube, CI users who were prelingually deaf produced the back vowel /u/ with a more anterior tongue position (Turgeon et al., 2015).

In the current study we found no significant difference in tongue position between the control- and blind-participant groups, unlike our findings in a previous study (Ménard et al., 2009). However, in the current study the vowels were presented in isolation so they may have been less variable than the vowels in carrier sentences that were used in the earlier study (Ménard et al., 2009). Since both studies have used the same recording technique (ultrasound) and the same machine (a Sonosite 180Plus), the difference might not be due to spatial or temporal resolution in data acquisition.

Lip geometry differed between groups. Blind participants had atypical lip opening values for vowel /i/. Since all three targeted vowels are commonly characterized as closed vowels, they should all be associated with a small lip opening. However, blind speakers presented larger lip openings than control and CI participants for the vowel /i/, which indicates that they produced this high/front vowel with a more open oral cavity. In addition, blind participants had lower lip protrusion values than controls and CI users. This suggests that, due to their visual deprivation, blind speakers were less able to use their lips (visible articulators) to successfully produce those rounded vowels. These findings agree with those in our earlier study (Ménard et al., 2009). Similarly, another earlier study also showed that articulatory strategies used by blind individuals to produce French phonemes were different from those of sighted participants (Ménard et al., 2013). Since the differences in lip dimension were robust and similar for isolated vowels (in the current study) and vowels in carrier sentences (in the earlier studies), (Ménard et al., 2009, 2013), this suggests that this lip geometry is more strongly associated with perception of speech than tongue position. We are currently investigating this in further studies.

Globally, our results are in line with the Perception-for-Action Control theory of speeh (PACT, Schwartz et al., 2002; 2012; 2007), which states that speech goals are multimodal perceptuo-motor units. When the speech production strategies associated to a given phoneme are acquired through impoverished perceptual conditions (such as in cases of sensory deprivation), the perceptual templates differ from those of typically developing individuals. Furthermore, as suggested by the kinematic measures, altered sensory input has impact on motor actions involved in speech production: CI and blind speakers used significantly different articulatory positions compared to typically developing speakers. The fact that only the lip dimension was affected in blind speakers confirms that less information on the control of orofacial actions in speech is acquired through the visual channel compared to the auditory channel. Nevertheless, the comparisons between the three speaker groups clearly shows that visual deprivation significantly alters the production-perception links in speech, in a way that is statistically comparable to auditory deprivation.

Conclusions

To summarize, in this study, we investigated the effects of auditory deprivation and visual deprivation on the strategies used to implement perceptual vowel goals. Several studies had provided evidence of such effects, but they focused on one sensory deprivation only. The current study offers a unique opportunity to compare the magnitude of those effects across sensory deprived populations using the same corpus and experimental setup. We found that speech production in deaf adults who were CI users affected tongue position, and this affected the quality of produced vowel targets. CI users produced smaller acoustic contrast between the front (/i/ and /y/) and back (/u/) vowels, and they also produced vowel targets for which the F2 values, which are associated with the point of articulation, were more dispersed and atypically high. CI users also presented F2-F1 values that were atypically elevated for the vowel /u/ (referring to the perceived backness), which is not surprising, since CI users had poorer ability to identify and distinguish the vowels they heard, which supports Perkell's assumption (Perkell et al., 2004) that auditory discrimination is linked to contrast production. In a previous study, we also reported atypical tongue position in CI users when they had to pronounce the/u/vowel and different acoustical data have also been obtained in young CI users when producing French vowels (Turgeon et al., 2015, 2017).

In agreement with previous studies in blind populations, the impact of visual deprivation on speech production in this study was also reflected in the visual articulators. As suggested by Ménard, Trudeau-Fisette, Cote and Turgeon (2016), since blind speakers cannot see a speaker's lip movements during speech productions, they tend to use different articulators or to use articulators in a different way than sighted individuals, to achieve their acoustic goals. In the current study, the articulatory strategies used by the blind participants seemed to be quite successful. In fact, although larger lip openings and smaller lip protrusions were observed in blind speakers for the rounded vowel (/y/ and /u/) and unrounded vowel (/i/), respectively, their acoustical results suggest that they were able to otherwise compensate for a lack of sight (they had F1 of /i/ that was smaller than F1 of /u/, and they had a larger contrast between /i/-/u/ and /y/-/u/ compared to CI users). Overall, there were no significant differences between the acoustic productions of the control participants and the blind speakers.

Acknowledgments

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Statement of interest

The authors report no conflicts of interest.

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