Cross-modal reorganization and speech perception in cochlear implant users

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Recent work suggests that once the auditory cortex of deaf persons has been reorganized by cross-modal plasticity, it can no longer respond to signals from a cochlear implant (CI) installed subsequently. To further examine this issue, we compared the evoked potentials involved in the processing of visual stimuli between CI users and hearing controls. The stimuli were concentric circles replaced by a different overlapping shape, inducing a shape transformation, known to activate the ventral visual pathway in human adults. All CI users had their device implanted for >1 year, but obtained different levels of auditory performance following training to establish language comprehension. Seven of the 13 patients showed good capacities for speech recognition with the CI (good performers) while the six others demonstrated poor speech recognition abilities (poor performers). The evoked potentials of all patients showed larger amplitudes, with different distributions of scalp activations between the two groups. The poor performers exhibited broader, anteriorly distributed, high P2 amplitudes over the cortex whereas the good performers showed significantly higher P2 amplitudes over visual occipital areas. These results suggest the existence of a profound cross-modal reorganization in the poor performers and an intramodal reorganization in the good performers. We interpret these data on the basis of enhanced audiovisual coupling as the key to a long-term functional improvement in speech discrimination in CI users.

Introduction

It has been shown that sensory activity supports neural development, and that sustained inactivity can induce a loss of responsiveness in various brain structures. This deprivation effect has been observed both in the visual (Wiesel and Hubel, 1965) and in the auditory (Rauschecker and Korte, 1993) modalities. Inversely, a sense can benefit from the deprivation of another (Kujala et al., 2000). Such cross-modal plasticity has been observed in both blind (e.g. Doucet et al., 2005b) and deaf individuals (Sadato et al., 2005).

A number of event-related potential (ERP) studies have reported larger ERP amplitudes and a more anterior distribution of brain activity in deaf individuals during visual tasks involving motion perception in the peripheral (Neville and Lawson, 1987) and central visual fields (Armstrong et al., 2002). In addition, functional MRI (fMRI) and magnetoencephalography studies revealed activity in temporal areas of deaf participants during a visual task (Bavelier et al, 2001; Finney et al, 2001; Finney et al., 2003). These results suggest recruitment of temporal and/or other brain regions in deaf subjects and hence, compensatory plasticity in the visual system. However, dissent exists about the exact nature of the visual processes that may undergo compensatory plasticity. Some authors did not find behavioural differences between the deaf and hearing individuals during visual tasks (Poizner and Tallal, 1987; Finney and Dobkins, 2001; Brozinsky and Bavelier, 2004; Heming and Brown, 2005) whereas others typically found lower thresholds in deaf adults in comparison with hearing controls on visual tasks that require attention (Parasnis and Samar, 1985; Emmorey and Kosslyn, 1996; Proksch and Bavelier, 2002).

Presently, profound deafness can sometimes be reversed by auditory stimulation from a cochlear implant (CI) (Ponton *et al.*, 1996). When surgeons first implanted CIs in deaf people, not much was known about the conditions necessary for a successful implantation. Indeed, the successes and failures of these early surgeries were instrumental in our current understanding of cerebral plasticity. We have learned that auditory awareness and speech perception recovery depend largely on the responsiveness of auditory areas in the central nervous system (Tyler and Summerfield, 1996). Deafness-induced changes in different cortical areas thus have important implications for rehabilitation with a CI and its integration as a communication tool can differ considerably according to the patient's individual experience (Giraud *et al.*, 2001). All studies agree that congenitally deaf children implanted early in age, when plasticity is greatest, perform better in open-speech perception tests than those who are implanted later (for review, *see* Robinson, 1998). Furthermore, adults who have been profoundly deaf since birth are usually incapable of understanding speech from CI stimulation (Busby *et al.*, 1993; Zwolan *et al.*, 1996).

While physiological mechanisms underlying performance with a CI are still not well known, cross-modal plasticity appears as a probable factor restricting access to auditory stimulation in long-term deafened individuals. Indeed, several studies have demonstrated activation of visual cortices induced by auditory stimuli in CI users. For instance, in a series of experiments, Giraud *et al.* (2001) used PET to investigate the effect of different meaningful auditory stimuli (speech, noises) on post-lingually deaf subjects who underwent a cochlear implantation. The patients exhibited a visual cortex activation that was not observed in controls. A very interesting outcome of these results is what they demonstrate about the impact of speech skills training programs: the cortical activation was less marked and less consistent in naïve than in rehabilitated patients. This observation suggests that these visual cortex activations are not only because of deafness-induced plasticity but also due to a brain reorganization related to functional learning of associations between visual cues (lip-reading, for instance) and oral speech, with a CI.

Naito *et al.* (1997) as well as Green *et al.* (2005) have shown that when CI users listen to oral speech, poor performers in speech recognition have less activation in the auditory association areas than do good performers and controls. This lack of activation in the temporal cortices could be explained by the invasion of competing synaptic inputs originating in other sensory systems over these formerly auditory territories in poor performers. In the same vein, Lee *et al.* (2001) have demonstrated that speech perception after cochlear implantation was better if the auditory cortex was hypometabolic before the surgery, suggesting that cross-modal activations of these areas could compromise the learning of language after a cochlear implantation. The authors suggested that the visual modality could overrun the auditory cortices in poor performers, but

nothing is really known about the brain activity evoked by non-linguistic visual stimulation in these patients.

Using fMRI, Wilkinson *et al.* (2000) have demonstrated that concentric stimuli that undergo radial transformations, similar to those used in this study, activate the ventral stream in normal adults when compared, for example, with rotating sinusoidal gratings. These stimuli are ideal to measure the visual reorganization following a period of deafness because (i) they activate the ventral stream up to, at least, the fusiform gyrus (Wilkinson *et al.*, 2000); (ii) they also activate the dorsal stream because of the transformational pattern (Tse, 2006) and (iii) they are relatively simple (they are defined by a mere quadruplet of parameters). In addition, contrary to faces, they are neutral, that is, they avoid familiarity effect or emotional responses. In a previous experiment we verified how neural responses to these transformational concentric patterns (TCPs) evolve over development in an evoked-potentials study (Doucet *et al.*, 2005*a*). We observed that the processing of these complex radially modulated stimuli induces brain activation that is not mature until 13 years of age. As these stimuli exhibit a protracted development, they are likely to be involved in brain reorganization associated with altered sensory experience (Mitchell and Neville, 2004). Hence, this particular visual stimulation could induce an altered representation in the brain of individuals deprived of a sensory modality for many years. This abnormal representation may be especially marked in those deaf individuals who are poor at recognizing speech with a CI.

In order to document this issue, a study of visual processing in two groups of CI users with differing speech perception capacities was carried out. We hypothesized that the visual evoked potentials (VEPs) observed in each group would be different, good performers being similar to hearing controls whereas the poor performers would show more activity in the temporal cortices than the control group.

Material and methods
Participants

Thirteen CI users and 16 hearing subjects took part in this study, which had been approved by local ethics committees (Université de Montréal and Centre Hospitalier Universitaire de Québec). All participants were right-handed. Informed written consents were obtained, in accordance with the Declaration of Helsinki.

All patients suffered from profound bilateral hearing loss: $\geqslant 87$ dB hearing loss in silence in the best ear without hearing aid within the 0.5–4 kHz range. The communication mode of CI subjects, prior to surgery, was oral/lip-reading and/or signed language. They were selected after cochlear implantation according to their performance on auditory speech perception for monosyllables, words and sentences. Seven subjects formed a group of good performers based on their ability to recognize speech without visual cues. The six others formed the group of poor performers based on their inability to perform in speech recognition tasks; these participants relied exclusively on sign language and lip-reading to communicate efficiently (*see* Table 1 for details). Within

Table I Clinical profile of CI patients

Subject	Sex	Age	Age at onset of deafness (years)	Cause of deafness	Degree of loss (dB threshold)	Deaf. duration (years)	CI duration (years)	Side of CI	Speech recognition with the CI (%)	Communication
S1	M	21	3	Unknown	Left = 118 Right = 105	16	2	L	73	Oral + lip-reading
S2	F	52	47	G.-Sjogren syndrome	Left = 110 Right = 105	2	3	R	98	Oral + lip-reading
S3	M	37	12–25 (progressive)	Hereditary	Left = 113 Right = 113	11–24	1	L	80	Oral + lip-reading
S4	F	42	27	Unknown	Left = 110 Right = 87	13.5	1.5	L	92	Oral + lip-reading
S5	F	18	0–15 (progressive)	Hereditary	Left = 93 Right = 105	1–16	2	R	85	Oral + lip-reading
S6	M	54	30–50 (progressive)	Hereditary	Left = 108 Right = 107	2–22	2	R	82	Oral + lip-reading
S7	F	25	0	Hereditary	Left = 107 Right = 107	23	2	R	92	Oral + lip-reading
S8	F	23	2	Meningitis	Left = 100 Right = 100	18	3	R	0	Sign language + lip-reading
S9	F	50	5	Chronic otitis media	Left = 118 Right = 115	44	1	R	0	Sign language + lip-reading
S10	F	41	2–12 (progressive)	Meningitis	Left = 117 Right = 117	28–38	1	R	0	Sign language + lip-reading
S11	M	18	0	Hereditary	Left = 97 Right = 93	16	2	L	0	Sign language + lip-reading
S12	M	62	10	Meningitis	Left = 113 Right= 115	52	1	L	0	Sign language + lip-reading
S13	M	49	0	Hereditary	Left = 105 Right= 110	47	2	L	0	Sign language + lip-reading

the good performers, three out of seven participants were pre-lingually deafened. All good performers were excellent at producing oral speech and they all preferred to communicate orally to others and read on lips in order to understand speech. Within the poor performers, four of the six participants were pre-lingually deafened. All poor performers were very efficient at communicating with LSQ (Quebec sign language); two of them used to teach sign language. They were also able to produce rudimental oral speech and they used lip-reading efficiently, when communicating with hearing people or watching television.

All subjects were implanted on the side of the poorest ear or the preferred side for those who were totally deaf on both sides. The data were recorded after CI surgery in all experimental subjects. A group of 16 neurologically intact normal hearing subjects, from 18 to 52 years of age, formed the control group.

Assessment of auditory capacities

All CI subjects underwent a thorough audiometric assessment, including pure tone detection, word identification in a closed-set paradigm, word and sentence recognition in an open-set paradigm, and speech tracking. The Test audiologique multimédia (Bergeron, 1998) was used to assess these speech perception skills. This is an interactive computer-based test battery developed for French Canadian CI users including a word identification test (38 mono and bisyllabic words), a word recognition test (48 mono- and bisyllabic words) and a sentence recognition test (60 common sentences). All test stimuli were presented by three different speakers (male, female and child) at 70 dBA in a quiet room.

Usually, most gains in performance with CI in adults with acquired deafness occur in the first 9–12 months of use (Tyler *et al.*, 1997). All subjects of this study had at least one year of experience with their device prior to the experiment and a 2 years follow-up was realized with two poor performers (S9 and S10) who had only a 1 year experience at the time of testing. At 3 years post-implantation, they were still not able to process open-set speech recognition, suggesting that these CI users probably still processed the information differently from the good performers.

Visual stimuli

The stimulus pattern consisted of a high contrast sinusoidal concentric grating (0.8 c/deg), subtending a stimulation field of 10 deg^2 (512 pixel^2) with duration of 500 ms, immediately followed by a star-shaped grating (Fig. 1) with duration of 500 ms. More specifically, the radially modulated pattern comprised five bumps and had an average concentric periodicity of 0.8 c/deg with a standard deviation of 0.071 c/deg (Doucet *et al.*, 2005a). Henceforth we will refer to these stimuli as TCP.

Visual-evoked potentials

Potentials were recorded from 40 scalp electrodes (10–20 system), mounted on a Quick Cap with Ag–AgCl electrodes referenced to linked ears. The ground electrode was located in front of Fz, in the midline of the forehead. The signal was amplified by a Nuamps system with a gain ×19 and recorded on a Neuroscan system with a sample rate of 1000 Hz and a bandwidth of 0.1–100 Hz. The horizontal electrooculogram, recorded as the voltage difference
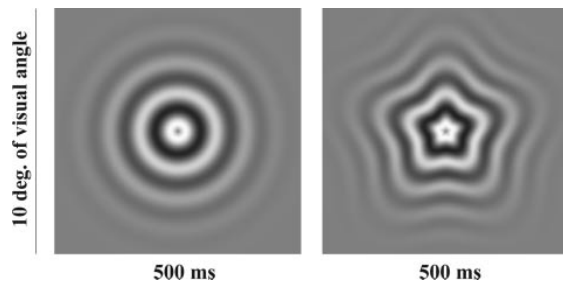
Fig. 1 High contrast sinusoidal concentric grating (0.8 c/deg), subtending 10 deg^2, followed, 500 ms after onset, by a similar grating radially modulated in frequency.

between electrodes placed lateral to the external canthi, was used to measure horizontal eye movements. The vertical electrooculogram, recorded as the voltage difference between two electrodes placed above and below the left eye, was used to detect eye blinks.

Procedure

After the installation of the electrophysiological cap, participants were comfortably seated in front of a high-resolution 17 inch CRT computer monitor at a viewing distance of 114 cm. A Macintosh G4 portable computer running a V-Pixx program controlled the experiment. Participants passively viewed the visual stimulus 150 times. They were instructed to fixate the centre of the stimulus.

Data analyses

Trials were analysed off-line over an interval beginning 100 ms prior to and ending 500 ms after the onset of the visual stimulus transformation. Data were digitally filtered (0–30 Hz) with a 24-dB cut-off. Each epoch was averaged across all trials and corrected for eye blinks; epochs with artefacts above 150 μV were discarded. The VEPs were averaged from at least 50 trials for each participant. Baseline was defined as the mean value of the averaged VEP trace from −100 to 0 ms relative to stimulus onset.

Results

The grand average ERP waveforms elicited by TCP stimuli are shown in Fig. 2 for the three groups at frontal (Fz), central (Cz), occipital (Oz), and left and right temporal (T5 and T6, respectively) electrode sites. For the three groups, VEPs were characterized by a P1 positive deflection occurring at around 100 ms after stimulus onset, followed by an N1 negative deflection at 150 ms and a P2 positive peak at 230 ms (Fig. 2). We calculated the peaks for each of the three components (P1, N1, P2) at maximum amplitudes recorded at the Oz location (occipital), where the latencies were shortest.

In a previous VEP study (Doucet *et al.*, 2005*a*), we showed the evolution of the brain response to these stimuli across age, from childhood to adulthood. Developmental changes were most marked for the N1 and P2 component, which are particularly sensitive to visual motion variations (Hoffmann *et al.*, 2001; McKeefry, 2001). The adult pattern for all three components in the Doucet *et al.* (2005*a*)

N1和P2是发育中的重要指标

study was similar to the pattern observed with the control group.

One-way ANOVA *P*-values were computed using SPSS version 11. Because of multiple comparisons, only *P*-values < 0.01 were considered as being significant. The latencies of the three components did not differ across groups. The P1 and N1 amplitudes also did not differ. The amplitude of the P2 component, however, was significantly larger at the occipital sites (Oz, O1 and O2) in good performers than in the other two groups [Oz = $F(2, 26) = 9.127$, $P < 0.001$; O1 = $F(2, 26) = 6.797$, $P < 0.004$; O2 = $F(2, 26) = 11.476$, $P < 0.0005$].

The topographical data were analysed using Brain Vision Analyser software version 1.05 (Brain Products, Munich, Germany). The mapping program allows for the representation of the actual voltage distribution on the scalp in a three-dimensional perspective. The topographical maps represent the brain activation at the maximum amplitude of the P2 component on each group of grand averaged evoked potentials. Back view maps were used with interpolation by spherical splines and manual scaling (0–5 μV). The scalp distribution of the P2 component is shown for the 40 electrodes in the three top topographical maps presented in Fig. 3. The two bottom figures illustrate, in the form of a colour gradient, the amount of underlying cortical activation in the comparison of each of the two experimental groups with the control group. Subtraction waves comparing the difference between the good performers and the controls and between the poor performers and the controls for five electrode sites [frontal (Fz), central (Cz); middle occipital (Oz); left temporal (T5) and right temporal (T6)] are also presented in this figure. *T*-tests, also conducted using Brain Vision Analyser software confirmed that the amplitude of the P2 component was superior in the occipital region of good performers than in hearing controls ($t \geqslant 2.09$; $P \leqslant 0.05$) whereas it was superior in anterior regions within the group of poor performers, in comparison with the control participants ($t \geqslant 2.09$; $P \leqslant 0.05$).

Discussion

This study shows that cross-modal cortical activity could theoretically explain the subsequent ability to process a newly introduced sensory modality. More specifically, the results demonstrate that responses to visual stimulation in CI subjects are related with their speech recognition abilities. Accordingly, in comparison with the control group, the group of CI users with limited speech perception capacities showed a profound cross-modal reorganization, involving more anteriorly distributed cortical activation following visual stimulation. For the same task, the better CI performers showed an enhanced brain activity within the preserved visual cortex. This reorganization could reflect, in the former, a recruitment of additional cortical areas to carry out visual tasks and, in the latter, a better use of visual cues to compensate for the imperfect CI auditory signal.
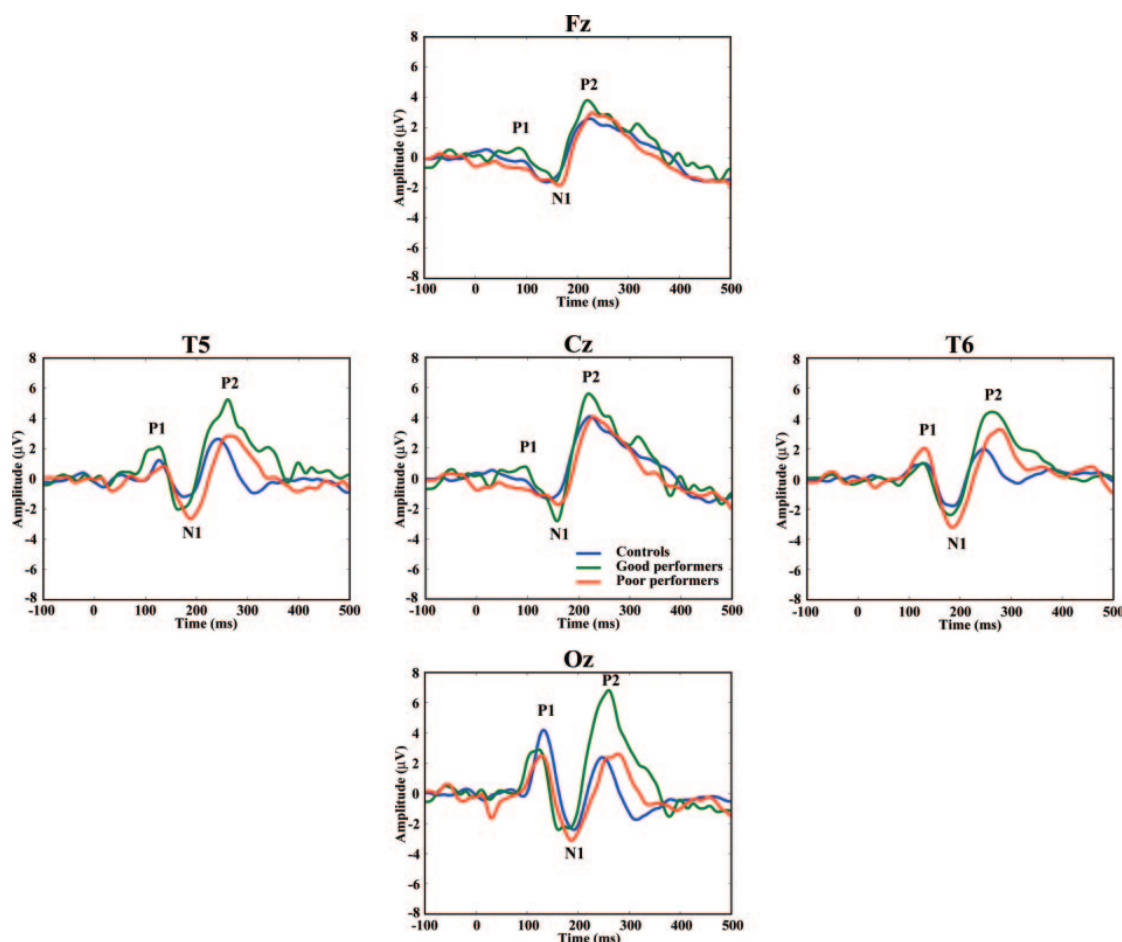
Fig. 2 Average waveforms of the three groups at five electrode locations (Fz, Cz, Oz, T5, T6). Blue lines represent controls, green lines, good performers and red lines, poor performers. Voltage (μV) is displayed on the *y*-axis and time (ms) relative to the stimulus change, on the abscissa.
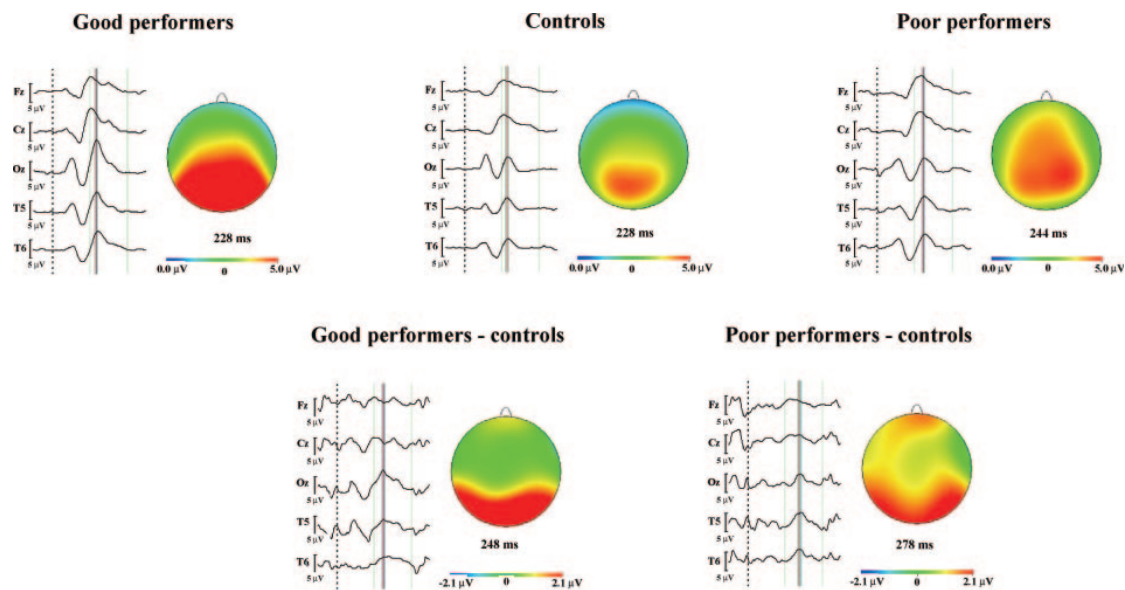
Cross-modal reorganization in CI users with poor speech perception capacities

In normal hearing subjects as well as in CI users with good speech perception capacities, the late cerebral response evoked to the visual stimulation was circumscribed around the primary visual cortex while it was more anteriorly distributed in poor performers. Thus, a larger part of the cortex was more activated in poor performers than in the control group for P2, that is, about 230 ms after stimulus onset, suggesting a larger recruitment of cortical areas for visual processing. Hence, in spite of renewed access to auditory stimulation from the CI, these individuals may still rely mostly on visual cues.

These results concur with those of Lee *et al.* (2001), which showed decreased hypometabolism in temporal cortex of poor CI users, possibly reflecting the appropriation of this region by visual processes during deafness. Similarly, in a FDG-PET study, Green *et al.* (2005) found, during an oral speech listening task, significantly higher levels of fluorodeoxyglucose in auditory areas of good CI users than in poor CI users. They also showed that duration of deafness had a significant negative effect both on speech perception outcome and cortical activation in auditory areas of CI users, a result which is congruent with our own observations. These findings as well as ours suggest that cross-modal recruitment of auditory areas could compromise the learning of speech after a cochlear implantation.

However, it is not clear whether this particular brain organization is due to deafness *per se* or to the practice of sign language (Neville and Lawson, 1987) that recruits the left and right temporal cortices of deaf people (Hickok *et al.*, 1996). In fact, a left hemispheric dominance found in deaf individuals was further shown to be present not only in deaf subjects who practiced American Sign Language but also in hearing signers (Bosworth and Dobkins, 2002), suggesting that experience with sign language alone was responsible for the reorganization. Our data are compatible with such an

Good performers   **Controls**   **Poor performers**

Good performers - controls   **Poor performers - controls**

Fig. 3 *Top*: Waveforms for five electrodes (Fz, Cz, Oz, T5, T6) next to topographical maps of the mean voltage amplitudes (μV—see middle colour bar) in good performers (*left*), controls (*middle*) and poor performers (*right*) groups, at the maximum amplitude of the Oz P2 component (see blue vertical line on the curves at left side of each map). *Bottom*: Subtraction waves next to topographical maps representing *t*-statistics of the differences between the good performers and controls (*left*) as well as the poor performers and controls (*right*).

interpretation as the poor performers had, on average, extensive experience with sign language, compared with the good performers (*see* Table 1 for individual profiles).

Intramodal reorganization in CI users with good speech perception

The second major outcome of this investigation is the saliency of the occipital activation in good performers. The P2 amplitude within the visual cortices recorded during the visual task was larger in the good performers when compared with each of the two other groups. Good performers therefore appear to take advantage of an enhanced brain activity within the preserved visual cortex to compensate for an imperfect auditory signal provided by the CI. The period of deafness preceding the cochlear implantation in these subjects (9.8–16.6 years on average) and the visual compensation associated with this deprivation could have reinforced the neural circuits within the primary visual areas. However, this deprivation period did not appear to be sufficient for the visual circuits to take over the auditory cortices as observed with poor performers, who had a longer duration of profound deafness before the surgery (34.2–35.8 years on average), and in whom the deafness appeared at an earlier age (3.2–4.8 years of age in poor performers against 17–23.9 years of age in good performers).

In a case study, Goh *et al.* (2001) observed that a very good CI user was better than normal hearing subjects at detecting visual cues during speech, whereas he was poorer

at detecting speech when only auditory cues were present. Moreover, this subject appeared to be equal to hearing controls in perceiving speech when auditory and visual cues were present. The authors concluded that this patient benefited more than controls from visual information in order to understand oral speech. Similarly, supra-normal brain responses to visual stimuli in our group of good performers can be interpreted as reflecting an enhancement of visual resources to complement speech auditory processing.

It is also noteworthy that Tyler *et al.* (1997) observed an increase in lip-reading ability in implanted children in a two-to-four-year follow-up, while the same children did not show any improvement in the auditory-alone condition within this time frame. Thus, introduction of a new auditory–visual context can bring new cues to decode lip movements and then support visual tasks involved in communication. This reinforces our hypothesis that good CI performers display better visual abilities related to communication abilities, and these are reflected in the electrophysiological measures.

Using $H_2^{15}O$-PET, Giraud *et al.* (2001) also observed an improvement of performance in both speech and lip-reading comprehension in the years following implantation. More specifically, the patients with the highest lip-reading scores were those with the strongest response in the visual cortex (V1 and V2) when listening to speech sounds. The authors explained this result by a mutual reinforcement of auditory and visual modalities. This cross-modal binding could

thus explain the greater activation in the visual cortices of good performers in this study. A lack of audiovisual association could also explain the poor performer's failure in rehabilitation with a CI and the weaker activations in visual cortices, compared with the good performers. The audio-visual coupling should thus be the key to a long-term functional improvement in speech discrimination.

Conclusions

This is the very first study carried out on the processing of visual information by CI users. Our results support the concept that limited auditory benefits from a CI could be, at least in part, related to the non-availability of cortical structures that should normally process the auditory information transmitted by the device because they have been recruited by another modality. They also demonstrate that visual areas can contribute to auditory function when the two modalities complement each other within the stimulus context. These results reflect therefore the influence of prior experience on intermodal plasticity and how visual processing by different CI users can reflect the involvement of cross-modal plasticity in the learning of an oral language.

Acknowledgements

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