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Audiovisual fusion and cochlear implant proficiency

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Abstract. *Purpose:* Recent studies suggest that cochlear implant (CI) users have a typical, and perhaps improved, ability to fuse congruent multisensory information. The ability to fuse incongruent auditory and visual inputs, however, remains to be fully investigated.
Methods: Here, performance on a classical audiovisual task (the McGurk effect) was assessed in seventeen cochlear-implanted, postlingually deaf individuals with varied degrees of auditory competency.
Results: In line with previous studies, our results revealed audiovisual fusion abilities that were within normal limits in CI users compared to normally-hearing (NH) participants. A different pattern of response emerged, however, when participants' responses were analyzed according to the degree of auditory proficiency with the CI. Although proficient CI users (pCI) and NH participants favoured auditory input when multisensory signals were not fused, only the non-proficient CI users (npCI) relied predominantly on visual cues to resolve audiovisual conflict. This pattern was found despite a similar percentage of fused percepts between pCI users, npCI users and NH participants.
Conclusion: These data show a remarkable level of similarity between pCI users and NH individuals in the perception of incongruent audiovisual information, suggesting that optimal auditory performance with the CI is associated with normal fusion of conflicting audiovisual input.

Keywords: Multisensory integration, cochlear implant, deadness, McGurk effect

1. Introduction

In everyday situations, speech understanding is achieved in an audiovisual mode that equates the congruent movement of the lips with matching auditory speech signals. In normally-hearing (NH) individuals, such intersensory redundancy speeds up and enhances perceptual accuracy, as a manifestation of the cooperative advantage that emerges from multisensory perception (McDonald et al., 2000; Teder-Sälejärvi et al., 2002; Frassinetti et al., Làdavas, 2002; Bolognini et al., 2005; van Wassenhove et al., 2005). In deaf individuals, intersensory perception is substituted by a process that favors visual strategies to improve speech recognition through lipreading (Tyler et al., 1997; Kaiser et al., 2003) or sign language (Neville and Lawson, 1987; Proksch and Bavelier, 2002; Brozinsky and Bavelier, 2004). This can lead to a behavioral advantage in the visual modality (see Bavelier et al., 2006), as well as extensive visual-to-auditory cross-modal plasticity in auditory cortex (Pettito et al., 2000; MacSweeney et al., 2002; Armstrong et al., 2002; Finney et al., 2003; Sadato et al., 2005).

It is possible to restore hearing in deaf individuals through the surgical implantation of a cochlear implant (CI), raising questions as to how the auditory and visual modalities interact following reafferentation. It has been repeatedly shown that most CI users integrate *congruent* auditory and visual information appropriately

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(e.g. Tyler et al., 1997; Kaiser et al., 2003; Geers, 2004; Moody-Antonio et al., 2005). It has also been suggested that CI users better integrate congruent audiovisual signals than NH individuals. Using an audiovisual speech recognition task in adult participants, Rouger and collaborators, (2007) found that that CI users had a greater capacity to integrate visual cues and distorted auditory signals, revealing greater speechreading abilities and audiovisual recognition performance. It may be an overstatement to generalize these findings and suggest that CI users display enhanced audiovisual abilities since multisensory integration has been predominantly explored in situations where the auditory and visual stimuli are equated. The ability of CI users to integrate *incongruent* multisensory information has, for its part, received less attention. Incongruency between auditory and visual inputs during speech recognition can lead to biased or illusory perception. In the McGurk effect (McGurk and MacDonald, 1976), a perceptual bias is introduced through the presentation of an incongruent lip movement accompanying an auditory speech signal leading to a fused percept of the visual and auditory inputs. For example, upon hearing /ba/ but seeing /ga/, most subjects will report hearing the fused percept /da/.

Three recent studies have specifically addressed the issue of how individuals with cochlear implants resolve audio-visual conflict in McGurk-like situations. Schorr and co-workers, (2005) tested 36 congenitally deaf children (mean age: 6 years) who had received a CI at least 1 year prior to testing on a classical McGurk task requiring verbal responses. In the incongruent condition, the auditory /pa/ was paired with the visual /ka/ resulting in most observers in the illusory perception of an auditory /ta/. In unimodal and bimodal congruent conditions, most normally hearing (NH) and CI children provided accurate auditory responses. Whereas bimodal fusion of the visual /ka/ and auditory /ta/ was consistent in the majority of NH children (57%), it was significantly lower in participants with a CI (20%). Furthermore, the pattern of answers was biased towards the auditory modality in NH children whereas it was biased towards vision in CI children. It was also found that the level of bimodal fusion leading to a “McGurk” percept in CI users was related to the time of cochlear implantation, where all participants showing clear and consistent bimodal fusion had receved their implant before 30 months of age. Taken together, this first set of data demonstrated that: i) bimodal fusion of the McGurk type is possible in cochlear implanted children, albeit generally weaker; *ii*) in non-fused trials, NH children are usually biased towards the auditory modality whereas CI children show a visual bias; and *iii*) the degree to which a CI user fusions incongrent audiovisual speech is dependent upon the age of implantation. Interestingly, the differences between NH and cochlear implanted children reported by Schorr et al., (2005) are reminiscent of those found between NH children and adults. Illusory audio-visual speech integration is weaker in children (Rosenblaum et al., 1997; Burnham and Dodd, 2004; Desjardins and Werker, 2004) and in trials in which no McGurk illusion is perceived, children will usually choose the visual input whereas adults preferentially choose the auditory input (McGurk and McDonald, 1976; Massaro et al., 1986). Further complicating the issue of speech fusion abilities in CI children, we have recently shown that bimodal fusion of incongruent audiovisual stimuli does not reach adult levels before the age of 10 (Tremblay et al., 2007). Indeed, children aged 5–9 display significantly less McGurk illusions than either 10–14 and 15–19 year olds and the frequency at which a child perceives the McGurk illusion is directly related to chronological age. Taken together, data in childen suggest that experience with the CI, as well as experience with language *per se*, is an important factor in determining the level to which incongruent audiovisual speech signals will be integrated. This highlights the need to evaluate McGurk-like interactions in *adult* CI users to mitigate the effects of brain maturation and speech experience on bimodal fusion.

Rouger and collaborators, (2008) presented a series of meaningless vowel-consonant-vowel dissylables to a group of 33 (mean age: 52 years) postlingually deaf adult CI users and 39 NH control participants to determine if a McGurk effect could be achieved in CI users. In congruent audiovisual and auditory only conditions, NH participants identified significantly more stimuli than CI users whereas performance was equal between groups in visual only trials. CI users perceived typical Mcgurk illusions but, similarly to children with a CI, responses tended to favor the visual modality, whereas auditory and visual inputs contributed equally to the final percept in NH individuals. The increased weight of visual input to resolve bimodal conflict in CI users was suggested to reflect i) heightened speech-reading abilities that were developed during pre-implantation deafness; and *ii*) elevated sensitivity to noise resulting in over-reliance on visual input to decipher speech signals in noisy environments (Rouger et al., 2008). These data were confirmed by Desai et al., (2008), who studied 14 NH listeners and 8 postlingually deafened adult CI users on a series of consonant-vowel audio-visual pairs. They again showed that CI users and NH partiticipants perceived a McGurk effect at a similar frequency, but CI users were biased towards the visual modality in McGurk trials whereas the opposite was true for NH participants. Interestingly, duration of implant experience, and not duration of deafness, was correlated with strength of the McGurk effect, suggesting that significant re-calibration of audio-visual integration occurs following cochlear implantation.

Taken together, these studies suggest that bimodal fusion of incongruent audiovisual stimuli is present in children and adult CI users despite a degraded auditory input, leading to increased reliance on visual cues to resolve bimodal conflict. The strength of this integration, however, appears to depend on experience with the CI suggesting possible post-implantation reorganization of sensory and integration mechanisms. In line with the aforementionned behavioral data, it has been shown that CI users activate early visual areas during speech listening (Giraud et al., 2001). The possible link between cortical plasticity and speech peceprion in CI users raises important questions since it has been shown that performance with the implant depends in part on the extent of cross-modal plasticity that occured prior to cochlear implantation (Lee et al., 2001; Doucet et al., 2006; Lee et al., 2007). For example, we reported that high levels of cross-modal plasticity were associated with poor speech perception abilities (Doucet et al., 2006) since a more anterior distribution of the event-related potential P2 component was found in CI users who were less efficient at processing auditory speech cues. In addition to plastic changes occuring prior and after cochlear implantation, several factors can also influence performance with the CI such as duration of deafness (Lee et al., 2001), communication strategy (i.e., familiarity with lipreading or sign language ability) used before implantation (Hirano et al., 2000) and onset of deafness (Naito et al., 1997; Giraud et al., 2001). All these factors interact and influence auditory perception following implantation (Lee et al., 2001; Lee et al., 2007), suggesting that multisensory integration in CI users may reflect the great variability in auditory perception that results from these variables.

To our knowledge, no study has explicitely investigated the link between auditory proficiency with a CI and bimodal fusion of incongruent audiovisual information. This is an important issue since it could be hypothesized that CI users in which auditory abilities are near-optimal would behave in a very similar manner to that of NH individuals since there would be no need for compensatory strategies in dealing with degraded speech signals. Diverging patterns of cross-modal plasticity of the kind described above could also differentially influence speech integration in CI users that have good hearing abilities and those who do not. Indeed, we have recently showed that presentation of visual stimuli (random dot motion or lip movement) during an auditory speech recognition task significantly impairs performance in non-proficient CI users only (Champoux et al., 2008), suggesting a detrimental effect of cross-modal plasticity on the *segregation* of conflicting auditory and visual information. It is an open question whether proficiency with the CI also impacts *fusion* of auditory and visual cues. In the present study, audiovisual integration in CI users was investigated with classical McGurk stimuli. Prior to testing, the auditory performance of each CI user was systematically evaluated with a bisyllabic speech recognition task and later related to audiovisual performance. Proficient and non-proficient CI users were compared to NH participants and the way in which conflicting visual and auditory cues was perceived (audiovisual, auditory-predominant, visual-predominant) was compared and related to CI proficiency.

2. Materials and methods

2.1. Participants

Seventeen adult CI users (7 males) aged 19 to 69 years participated in the study. They were recruited through the Raymond-Dewar Institute, a center for deafness and communication readaptation. The clinical profile of each CI user is presented in Table 1. In all CI users, the principal mode of communication was oral/lip-reading. All CI users suffered from profound bilateral hearing loss and were post-lingually deafened. The CI users had received their implant from 1.5 to 16 years before the experiment. The large majority of them ($n = 15$) reported progressive hearing loss during their life, until implantation. The etiology of hearing loss was various and unknown in many cases. Twelve normal-hearing adult controls (7 females, 5 males) aged 20 to 28 were also recruited for the experiment to validate stimulus efficiency and reveal a “normal-answering” pattern. They had no declared neurological disorder, and their vision was normal or corrected to normal. The project had been reviewed and approved by three Scientific and Ethics committees (Sainte-Justine Hospital, Raymond-Dewar Institute and University of Montreal). All participants gave written informed consent before participating in the study.

Table 1
Clinical profile of CI patients

Participant	Sex	Age	Age at onset of deafness (years)	Cause of deafness	Deafness duration (years)	CI duration (years)
P1	F	19	0–16 (progressive)	Unknown	1–16	3
P2	F	43	27–38 (progressive)	Unknown	2–13	3
P3	F	54	25–52 (progressive)	Unknown	1–27	2
P4	M	59	49 (sudden)	Unknown	1	9
P5	M	66	0–64 (progressive)	Unknown	1–64	2
P6	F	58	30–52 (progressive)	Hereditary	1–22	6
P7	F	65	20–40 (progressive)	Unknown	22–42	3
P8	F	65	0–40 (progressive)	Unknown	1–60	5
NP1	M	54	11–51 (progressive)	Unknown	1–40	3
NP2	F	44	7–42 (progressive)	Unknown	35	2
NP3	F	58	6–11 (progressive)	Unknown	44–49	3
NP4	M	48	0–30 (progressive)	Hereditary	15–45	3
NP5	F	48	4–30 (progressive)	Unknown	10–36	8
NP6	F	54	5–51 (progressive)	Infectious	1–46	3
NP7	M	25	0–3 (progressive)	Hereditary	6–9	16
NP8	F	69	0–50 (progressive)	Infectious	1–66	3
NP9	M	43	4–40 (progressive)	Unknown	1–36	3

P: proficient CI users; NP: non-proficient CI users.

2.2. Procedure

Participants were seated in a semi-dark anechoic room with the head on a chin rest located 57 cm from a computer screen (and speakers) where the stimuli were presented. The testing was done in a single session. The visual stimuli were presented either at fixation or at 5 degrees below fixation, on a 17-inch Viewsonic computer screen using Presentation (Neurobehavioral Systems) software. Prior to the McGurk task, the CI users had their auditor abilities evaluated, using a list of fourteen bisyllabic words. CI users were then divided into groups of non-proficient (npCI; $n = 9$) and proficient (pCI; $n = 8$) CI users based on a criterion of 70% correct responses. Percentage of correct answers on the bisyllabic word task for each npCI participant was: 0%, 23%, 23%, 30%, 30%, 55%, 55%, 58%, 60% and for each pCI participant was: 70%, 80%, 83%, 83%, 83%, 88%, 93%, 98%). Although one participant was not able to provide a single correct answer in this task, data were included in the analysis since performance on the easier *auditory alone* control condition on the actual experiment (see below) was well within normal limits (80% correct).

The McGurk task was done in two steps. First, combined audiovisual stimuli and control auditory-only stimuli with a static face (lips not moving) were presented. The bimodal presentation of the stimuli included congruent audiovisual /ba/, audiovisual /ga/ and the McGurk illusion which consisted of auditory /ba/ and visual/ga/ (which is known to lead to a /da/ percept illusion). The visual input consisted of the lower part of a young woman's face pronouncing the syllable. The stimulus was designed so that lip movements could be clearly seen. Each condition was presented both on the fixation point and on a parafoveal location (5° under the fixation point). Participants were instructed to look at a fixation cross in the center of the screen that was presented before each trial. A stimulus was presented right after the cross had disappeared. Observers were told to look carefully and to repeat the syllable they had heard as clearly and precisely as possible. All conditions were performed ten times, in a random order. A control lipreading condition was performed immediately after. In this task, unimodal visual /ba/ and /ga/ lip movements were shown. Participants were instructed to lipread and choose if the person on the screen had said /ba/ or /ga/. The stimuli were presented on the fixation point only and each condition was repeated 20 times.

For control conditions (auditory alone, visual alone, audiovisual congruent), the percentage of correct responses was computed and subjected to a mixed ANOVA with group (npCI, pCI, NH) as the between-subjects factor and condition (auditory alone, visual alone, audiovisual congruent) as the within-subjects factor. For incongruent audivovisual presentations, the percentage of each type of response (auditory, visual, fusion) was computed and subjected to a mixed ANOVA with group (npCI, pCI, NH) as the between-subjects factor and response (auditory, visual, fusion) as the within-subjects factor.

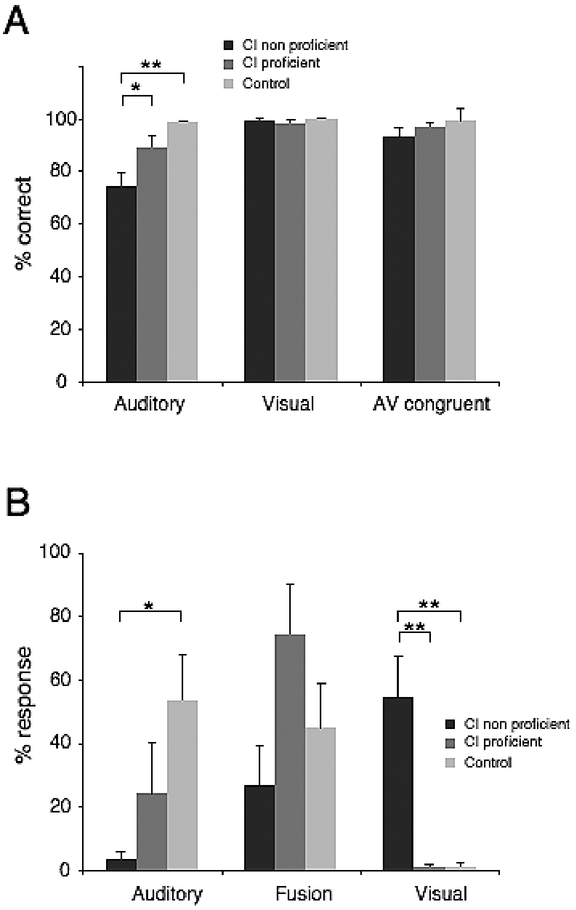

Fig. 1. A) Percent correct identification of stimuli in the visual, auditory, and congruent audiovisual trials for the three groups. B) Response type in the incongruent audivovisual trials. $^{*}p < 0.05$; $^{**}p < 0.001$.

3. Results

3.1. Control conditions

The percent correct reponses in each control condition is presented in Fig. 1A. In the *visual alone* and *audiovisual congruent* conditions, the three groups performed equally well (correct identifications $> 93\%$). As expected for the *auditory alone* condition, correct identifications were reduced in npCI (74% correct) compared to pCI (89% correct) and NH (99%). A mixed ANOVA with GROUP and CONDITION as factors confirmed these observations. The were main effects of CONDITION (F $= 26.35$; $p < 0.001$) and GROUP (F $= 12.30$; $p < 0.001$) and the interaction was also significant (F $= 9.84$; $p < 0.001$). Differences between each level of the CONDITION factor were further investigated with separate ANOVAs for each group of participants. There was a significant effect for the *auditory* condition only (F $= 13.78$; $p < 0.001$), in which the npCI group gave significantly less correct answers than the pCI ($p = 0.03$) and NH ($p < 0.001$) groups.

3.2. Audiovisual incongruent condition

The percentage of each type of answer (auditory, fusion, visual) is presented in Fig. 1B. Contrary to control conditions, the pattern of answers varied widely between groups. Auditory (npCI: 4%, pCI: 24%, NH: 54%), fusion (npCI: 27%, pCI: 74%, NH: 45%) and visual (npCI: 54%, pCI: 1%, NH: 0%) responses were not equally distributed between groups. A mixed ANOVA with GROUP and RESPONSE as factors revealed a main effect of GROUP (F $= 4.38$; $p = 0.02$) and a significant interaction between factors (F $= 5.05$; $p = 0.01$). Differences between each level of the RESPONSE factor were further investigated with separate ANOVAs for each group of participants. There was a significant effect for the *auditory* (F $= 4.21$; $p = 0.03$) and *visual* (F $= 18.03$; $p < 0.001$) responses. Participants in the npCI group gave significantly more visual answers than pCI ($p < 0.001$) and NH ($p < 0.001$) participants. Additionally, npCI subjects gave significantly less auditory answers than the NH participant ($p = 0.03$). Most importantly, there was no statistically significant group difference in the percentage of *fusion* answers in the incongruent audiovisual condition ($p > 0.05$).

When data from the pCI and npCI users were analyzed together and compared to NH participants, the proportion of fused audiovisual answers (McGurk effect) was highly similar to that found in NH individuals (NH: 45%, CI: 49%). However, a mixed ANOVA with GROUP (CI, NH) and RESPONSE (auditory, visual, fusion) as factors revealed a significant interaction between factors (F $= 3.63$; $p = 0.04$; Fig. 2). Differences between each level of the RESPONSE factor were further investigated with separate t-tests for the two groups of participants. Participants in the CI group gave significantly more visual answers than NH ($p = 0.02$) participants. Additionally, CI subjects gave significantly less auditory answers than NH participant ($p = 0.01$).

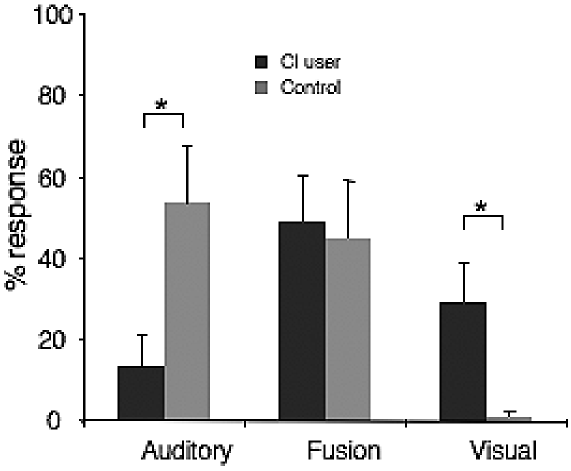

Fig. 2. Response type in the incongruent audivovisual trials when pCI and npCI users are grouped together. $^*p < 0.05$.

4. Discussion

The aim of the present study was the investigation of audiovisual fusion performance in CI users with varying degrees of auditory proficiency. In line with previous studies (Rouger et al., 2008; Desai et al., 2008), the proportion of fused audiovisual answers (McGurk effect) was highly similar to that found in NH individuals when data from the pCI and npCI users were analyzed together. Furthermore, when auditory and visual signals were not fused, NH participants favoured auditory information whereas the opposite bias was found in CI users. Considering the large variability of auditory recognition performance in CI users, however, the link between CI proficiency and audiovisual integration was explicitly investigated. Our results extend previous findings by showing that significant differences emerge between groups when pCI and npCI users are analyzed separately. Proficient CI users showed an auditory bias highly similar to that found in NH individuals when auditory and visual signals were not integrated. Contrary to previous findings (Rouger et al., 2008), our data suggest that when the auditory input is at a near optimal level, CI users display a pattern of response very similar to that of NH controls. It is only when the auditory input is degraded due to sub-optimal performance with the CI that answers are biased towards the visual modality. In light of their relatively weak auditory discriminative capabilities, it is not surprising that npCI users rely principally on visual cues to decipher speech signals in bimodal presentations. However, considering the robust differences in the way pCI and npCI users discriminate conflicting speech signals, it is somewhat surprising that audiovisual fusion in the McGurk trials did not differ between groups.

According to the "inverse effectiness" principle (Meredith and Stein, 1986), the ambiguity from a weak sensory input can be compensated for by another sensory modality. Accessing information coming from different senses increases speech discrimination performance when the cues from each modality are *congruent* (Perrott et al., 1990; Hughes et al., 1994; Frens et al., 1995). This principle has been showed in NH and hearing impaired individuals (Grant et al., 1998; Sekiyama et al., 2003; Ross et al., 2007), but also in deaf individuals (Alegria and Lechat, 2005) and CI users (Rouger et al., 2007). Indeed, even a negligible visual cue can greatly increase speech comprehension when the auditory signal is degraded (Zekveld et al., 2008). However, it has also been shown in NH participants that fusion of *incongruent* multisensory information decreases when the sensory cues are degraded (MacDonald et al., 2000; Alsius et al., 2005). In the present experiment, unisensory and attentionnal resources towards the auditory modality were certainly degraded in npCI users since they had presented poor performance levels in an auditory-alone discrimination task and a clear bias towards the visual modality in bimodal trials. Still, npCI users displayed normal levels of audiovisual integration in the McGurk trials compared to both pCI users and NH controls. For example, three npCI users with very poor auditory word discrimination scores (10% or less), were better at fusing auditory and visual information to achieve a McGurk effect than NH individuals or the most proficient CI users. In line with previous data (Rouger et al., 2008), these findings suggest a normal ability to integrate incongruent auditory and visual information even when auditory speech cues are greatly diminished.

Cross-modal reorganization has been repeatedly shown to occur in the profoundly deaf (e.g. Nishimura et al., 1999; Finney et al., 2003; Sadato et al., 2005; Bavelier et al., 2006). In these individuals, the use of a CI increases activity in auditory cortical areas (Naito et al., 1995; Okasawa et al., 1996; Wong et al., 1999: Lee et al., 2001; Lee et al., 2007), and modifies the response to auditory speech information (Giraud et al., 2000). In addition, it has been shown that CI users display atypical low-hierarchical visual activity during speech recognition tasks (Giraud et al., 2001). Such cross-modal interactions tend to increase with CI use (Giraud et al., 2001; Desai et al., 2008), suggesting a possible "mutual reinforcement of hearing by vision and vision by hearing" following cochlear implantation

(Giraud et al., 2001). By showing similar audiovisual fusion abilities among pCI and npCI users, our data are consistent with the notion of reciprocal auditory/visual reinforcement generated by cross-modal interactions. Indeed, it appears that CI users can compensate for the lack of robust auditory information by the increased use of visual cues. In the *visual only* condition, we did not find differences between any of the three groups. This is at odds with previous reports showing enhanced lipreading abilities in CI users (e.g. Rouger et al., 2007). The present data are consistent, however, with those of Rouger et al., (2008) who reported identical *visual only* performance in CI users and hearing controls using visual stimuli with "meaningless phonetic structure". There are at least two possible explanations for this discrepancy. First, the difficulty level of the word recognition task may be too low to reveal any significant differences. A discrimination task may be better suited to discriminate between groups (Strelnikov et al., 2009). Second, the fact that the *visual only* task was always performed after the audiovisual trials in the current study may have had an impact on the lipreading performance.

In the congenitally deaf cat (CDC), restoration of auditory input through a CI leads to recruitment of auditory areas that is highly dependent on age at implantation. Following a sensitive period of approximately five months, the development of long-latency responses is reduced and size of activated auditory areas is smaller compared to early-implanted animals (Kral et al., 2002). This is similar to the critical period of 4–5 years that has been found in human subjects (Fryauf-Bertschy et al., 1997) and data using McGurk-type stimuli showing that clear and consistent bimodal fusion is achieved in children who received their implant before 30 months of age (Schorr et al., 2005). It has been suggested that activity-dependent synaptic modifications (including synaptogenesis) cannot be achieved properly in congenital deafness, resulting in a naïve auditory cortex that does not respond in a suitable fashion to the introduction of auditory input following CI implantation (Kral et al., 2007). Since all our participants were implanted as adults, it is possible that variations in altered properties of auditory cortex prior to implantation partly explains the diverse pattern of behavioral responses that was observed in multisensory integration. Animal studies are needed to elucidate the cellular mechanisms that explain how plastic changes, both pre- and post-implantation, affect the integration of audiovisual inputs.

It has been suggested that rehabilitation strategies should be biased towards the visual modality since CI users show enhanced capabilities to integrate congruent auditory and visual information (Rouger et al., 2007). Because bimodal training can enhance unimodal perception, it may be useful to take advantage of the audiovisual abilities of CI users to increase auditory function (Rouger et al., 2007). Whereas our data generally support the idea that CI users would benefit from audiovisual integration training, it would appear that such an approach may not be beneficial to every user in every situation. Indeed, proper sensory scene analysis is based on both efficient *integration* and *segregation* processes. The npCI users as well as pCI users certainly benefit from visual input in congruent audiovisual situations. However, a recent study has shown that, in specific contexts, visual stimuli can be detrimental to auditory processing in CI users whose auditory performance is less than optimal (Champoux et al., 2008). Indeed, it appears that certain visual signals can hinder auditory processing when the visual input has to be ignored, such as when lip movements do not match what is heard (e.g. watching a translated movie, watching someone talking while listening to another, etc.). Taken together, these data show that although visual signals can facilitate speech perception in CI users in congruent audiovisual conditions, it might also hinder speech discrimination performance in some CI users when audiovisual inputs need to be segregated. As such, we suggest that that multiple aspects of multisensory processes following auditory reafferentation need to be investigated to establish which strategy is optimal for rehabilitation.

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