Phonological processing in post-lingual deafness and cochlear implant outcome

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Abstract

Cochlear implants work well, yet the outcome is not fully accounted by the data routinely available to the clinician, and remains unpredictable. A more in-depth understanding of the neural mechanisms that determine the clinical recovery after cochlear implantation is warranted, as they may provide the background for an accurate individual prognosis. In this study in post-lingually deaf adults, we show that while clinical data offer only prognosis trends, fMRI data can prospectively distinguish good from poor implant performers. We show that those deaf cochlear implant (CI) candidates who will become good performers rely on a dorsal phonological route when performing a rhyming task on written regular words. In contrast, those who will become poor performers involve a ventral temporo-frontal route to perform the same task, and abnormally recruit the right supramarginal gyrus, a region that is contralateral to classical phonological regions. These functional patterns reveal that deafness either enhances "normal" phonological processing, or prompts a substitution of phonological processing by lexico-semantic processing. These findings thus suggest that a simple behavioural pre-operative exploration of phonological strategies during reading, to determine which route is predominantly used by CI candidates, might fruitfully inform the outcome.

Key words: cortical plasticity, dual route, fMRI, hearing loss, supramarginal

Introduction

Cochlear implants (CI) work well in very young congenitally deaf children and in adults who become deaf after language acquisition (post-lingual deafness). Yet, speech comprehension levels can be highly variable (Lee et al., 2005), and determining who will benefit from an implant remains difficult in both populations of CI candidates. While the duration of auditory deprivation largely accounts for the outcome of cochlear implantation in congenitally deaf children (O'Donoghue et al., 2000; Sarant et al., 2001), it only imprecisely determines future speech comprehension performance in post-lingually deaf adults (Blamey et al., 1996; Green et al., 2007; Proops et al., 1999; van Dijk et al., 1999). Finding alternative predictors of CI outcome in the latter population is therefore a critical and timely issue.

Clinical observations indicate an important role of cognitive factors in post-CI speech perception (Pisoni and Cleary, 2003). As no specific cognitive ability has been identified as a determinant factor, functional neuroimaging in candidates for cochlear implantation could offer new insights in this respect. By identifying activation patterns prior to implantation that correlate with speech performance subsequent to implantation, functional explorations in CI candidates should pinpoint cognitive processes or dysfunctions that facilitate or constrain the clinical outcome. Speech performance with CI has been found to correlate with local cerebral metabolic activity at rest measured prior to cochlear implantation (Lee et al., 2001; Lee et al., 2007a; Lee et al., 2004). In both children and adults, those CI candidates with higher resting metabolism in the dorsolateral prefrontal cortex become good implant users, while those with higher metabolism in ventral temporal regions tend to become poor users (Giraud and Lee, 2007; Lee et al., 2007a). This general profile suggests that two fundamentally different cognitive strategies are adopted during post-lingual deafness, a bad one based on global pattern identification by ventral brain regions, and a good one based on dynamic stimulus combination by dorsal brain regions (Aparicio et al., 2007; Ziegler et al., 2008). Relating increased resting metabolism to any cognitive function, however, remains highly speculative and calls for dedicated functional studies.

Post-lingually deaf adults with progressive hearing loss increasingly rely on speechreading for oral communication (Lee et al., 2007b; Rouger et al., 2007). Yet, due to the progressive lack of auditory inputs, phonological representations deteriorate, implying that correspondence between visemes and phonemes is bound to degrade (Andersson et al., 2001; Schorr et al., 2005). In the absence of auditory cues, speech reading alone does not permit sufficient disambiguation of phonetic contrasts to make sense of auditory speech, and cochlear implantation becomes necessary. In this study, we hypothesized that the quality of residual phonological processing plays a role in the way a patient will be able to use vocoded signals. We assumed that functional neuroanatomy associated with visual phonological processing in post-lingually deaf candidates to CI could predict the way they perceive speech sounds after implantation. We therefore set out to explore inter-individual variability in brain activations during a rhyming task performed on written speech.

In normal subjects, normal-hearing in particular, reading involves two different routes for the processing of regular and irregular words (Aparicio et al., 2007; Ischebeck et al., 2004; Ziegler et al., 2008). This dual route model assumes that reading regular words relies on a grapheme-to-phoneme conversion that uses a phonological assembly, while reading irregular words accesses stored lexical properties by a semantic process (Aparicio et al., 2007; Ziegler et al., 2008). These two routes have common input regions in the ventro-temporo-occipital cortex, but diverge downstream. While the indirect route (regular words) involves posterior and dorsal connections between BA 9/44 and BA 40, the direct route (irregular words) relies on anterior and ventral connections involving BA 45 and BA 21 and 22 (Aparicio et al., 2007; Booth et al., 2006). In post-lingually deaf adults, a progressive decline in the accuracy of auditory-phonological representations could slowly bias the approach to written material towards the use of the direct route, hence bypassing the grapheme/phoneme phonological stage for the benefit of a more global type of recognition that grants direct semantic access.

We therefore predicted that upon performing a phonological task on written material those post-lingually deaf subjects who disengage from the indirect phonological route might not so readily restore phonological access when implanted, which in turn should compromise speech rehabilitation. We expect the results of this prospective study to indicate whether phonological processing during reading could be an informative cognitive predictor of cochlear implantation outcome.

METHODS

Subjects (Table 1)

Sixteen adults participated in an fMRI study that was approved of by the local ethics committee (CPP, Sud-Est IV, Centre Léon Bérard, Lyon, France). Written informed consent was obtained from all participants. The subject groups were composed of eight post-lingual profoundly deaf CI candidates (6 women and 2 men, mean age ± s.d = 52.0 ± 15.1 years), who were candidate for a cochlear implantation, and eight age-matched normal-hearing controls (4 women and 4 men, mean age ± s.d = 46.6 ± 10.4 years). All subjects had normal or corrected-to-normal vision, no history of neurological pathology and were all right-handed according to the Edinburgh handedness inventory (Oldfield, 1971). All CI candidates had progressive sensorineural hearing loss. In two of them the evolution from mild to profound deafness was more abrupt than in the others, and then stayed stable for many years and until this study was performed (subjects numbered 7 and 8, Table 1). CI candidates 1 to 6 met the classical criteria for cochlear implantation, *i.e.* average of 0.5, 1, 2 kHz hearing threshold >90dB and <30% sentence recognition score with best fitted hearing aids (1995), and no word recognition using a list composed of three-phoneme monosyllabic words presented at a hearing level of 60 dB (HL) (Lafon, 1964) with best-fitted hearing aid. CI candidates 7 and 8 were referred to cochlear implantation in agreement with recently extended indications for implantation (Cullen et al., 2004). They had residual word recognition in the Lafon test (Lafon, 1964) with best-fitted hearing aid at the moment of the fMRI experiment. Given their outlier status with respect to deafness evolution and residual word recognition, these two subjects are marked in colour throughout the figures (CI candidate 7 in green and CI candidate 8 in red). These CI candidates present a clinical interest as they illustrate the variability physicians are currently confronted with. To assess individual history of deafness we report separately in Table 1 hearing loss duration, *i.e.* the time elapsed since subjective auditory acuity decrease leading to the use of hearing aids, and deafness duration, *i.e.* the time elapsed since the post-lingually deaf subjects could no longer communicate by hearing, even with the best-fitted hearing aids. Deafness duration for CI candidates 1 to 6 varied from 4 to 48 months, and reached 216 and 360 months for CI candidates 7 and 8, respectively. None of the 8 CI candidates used sign language, and they all relied on speechreading and written language for communication. Only seven received an implant. CI candidate 7 withdrew for personal reasons. Two CI candidates (3 and 8) were implanted with a Cochlear device (Melbourne, Australia) and the others with a MXM (Vallauris, France). Word recognition scores were measured six months after implantation using the Lafon test (Lafon, 1964)). Candidates were sub-divided, according to their word recognition scores after cochlear implantation, in poor (scores < 50%) and good performers (scores ≥ 70%, including Patient 3 (69%)).

Experimental paradigm

fMRI data were acquired during a phonological task in controls and prior to surgery in candidates for CI, and were related to post-operative word recognition scores in the latter. We subsequently performed multiple regression analyses as shown in Figure 1 between the fMRI data and the following factors: 1) phonological performance on a reading task obtained during fMRI, 2) deafness duration and hearing loss duration and 3) auditory word recognition scores at 6 months after cochlear implantation.

Imaging parameters for fMRI experiment

Gradient echo-planar fMRI data with blood oxygenation level dependent contrast were acquired with a 1.5T magnetic resonance scanner (Siemens Sonata, Medical Systems, Erlangen, Germany) with standard head coil to obtain volume series with 33 contiguous slices (voxel size 3.4 x 3.4 x 4 mm, no gap, repetition time 3.15 s, echo time 60 ms) covering the whole brain. Earplugs (mean sounds attenuation of 30 dB) and earmuffs (mean sounds attenuation of 20 dB) were provided both to controls and deaf subjects to equate experimental environment. We acquired 458 functional images in two runs per subject.

fMRI design and phonological tasks

Subjects performed a rhyming task that consisted in comparing the ending of two visually presented common regular French words. The material involved three possible phonological endings (sõ/, /zõ/ or /s[e˜]/) with different orthographic spellings (e.g., garçon /garsõ/, poisson /pwasõ/, médecin /mèds[e˜]/, coussin /kus[e˜]/ and prison /prizõ/, gazon /gazõ/), so that judgement could not be based on orthography but solely on phonology. Subjects were requested to determine if words rhymed. Word pairs were either simultaneously presented on the screen (Condition 1), or sequentially one after another on different screens (Condition 2, one-back task). Conditions were randomized across subjects and subsequently pooled for statistical analyses, as they did not show statistically significant differences. Subjects gave their response by button press (left button if rhyming, right button if not). For each condition, a reading task with a left button press served as a cognitive baseline. To ensure that our results were specific to phonological processing and not influenced by decisional or attentional capacity, subjects also performed a semantic control task consisting in categorizing presented words in animal, human, and inanimate. The fMRI experiment comprised two runs of twelve 34s-blocks, each with seven stimuli presented at a rate of 1 every 4 seconds (three blocks for each condition). A screen showing written instructions preceded each block. Between each block, subjects viewed a 30 seconds black screen. All subjects performed a 30 minutes training session using Presentation software version 9.90 (Neurobehavioral system, Inc., Albany, CA, USA). We recorded rhyming and semantic performance and related reaction times. The percentage of correct trials for the rhyming task is referred to as “phonological score” in the following sections.

Statistical analyses

Phonological scores and reaction times were compared across groups using non-parametric Mann-Whitney tests. Correlations between pre-CI clinical parameters, *i.e.* deafness/hearing loss duration, behavioural parameters (phonological performance) and post-CI word recognition scores were tested using non-parametric one-tailed Spearman’s tests (Stat view 5.0, SAS institute, Grenoble, France). We tested the hypotheses that post-CI word recognition depends 1) on the duration of deafness and hearing loss and 2) on pre-CI phonological performance. These analyses showed that hearing loss duration accounted better than deafness duration for individual global history of deafness and for clinical outcome. Thus, hearing loss duration was subsequently used in the fMRI dataset analyses.

The fMRI data were analyzed using SPM5 (Statistical Parametric Mapping, Centre for Neuroimaging, London, UK, http: //www.fil.ion.ucl.ac.uk/spm) in a Matlab 7.1 (Mathworks, Natick, MA, USA) environment and displayed using MRIcron software (www.sph.sc.edu/comd/rorden/mricron). We performed standard preprocessing (realignment and unwarping, normalization and spatial smoothing with an 8-mm full width at half-maximum Gaussian kernel), and calculated contrast images in each single subject for 1) phonological task *versus* baseline and 2) phonological *versus* semantic task. We performed group analyses of the contrast phonological task *versus* baseline and semantic task (one sample t-test). We then entered contrast images into a regression analysis to test whether neural activation varied as a function of word recognition scores after six months of implantation. We set the threshold for the regression at $p=0.001$, uncorrected, but report only those clusters that were also significantly activated in the main effect of phonology (depending on the group) at $p=0.0001$, corrected, thereby ensuring that the observed effects belong to “phonology” networks. For display purposes we extracted individual beta values in the phonological (*versus* baseline) task (in both groups), we divided CI candidates data according to postoperative CI outcomes (below 50%, above 70%), and plot them in relation with those from control subjects. In a second step, we mapped correlations between activation during the phonological task and clinical data, i.e. deafness and hearing loss duration. We report results thresholded at $p<0.001$, uncorrected (same criteria as above). We extracted the beta values from the obtained clusters and tested them for another correlation with behavioural data that had not previously served for the mapping, i.e. post-operative word recognition scores using a *post-hoc* non-parametric Spearman test ($p < 0.05$).

Group differences (group-by-task interactions) between CI candidates and controls were also explored using a two sample *t*-test and reported at a p=0.001 statistical threshold, uncorrected. Given the small sample size, group differences were further checked using a *post-hoc* non-parametric Mann-Whitney test, with threshold for significance set at p = 0.05. Regressions with behavioural data (not previously used for mapping, i.e., phonological scores and post-CI word recognition) using a non-parametric Spearman test (p < 0.05), after extracting values were also tested.

By default, all statistical analyses were performed in the six totally deaf subjects with the two outliers CI candidates colour-coded in the figures. Statistics including these CI candidates are further provided (n = 8 before for results before CI, n = 7 for those after CI as one of the patients withdrew).

RESULTS

Behavioural data

CI candidates and controls performed equally well in the rhyming (Figure 2A and B) and the semantic tasks (no significant difference in accuracy and reaction time). This validated the experimental design showing that CI candidates did not face a too difficult task, which could have prompted the use of inappropriate compensation strategies (Raz et al., 2005).

Correlations between behavioural and clinical data.

Phonological performance tended to decrease with time elapsed since the onset of hearing loss (rho = -0.7, p = 0.036, for n =6; and rho = -0.5, p = 0.09, for n = 8, Figure 3A), while time elapsed since the onset of profound deafness did not appear to influence phonological scores (rho = -0.52, p = 0.2, for n =6; and rho = -0.33, p = 0.4, for n = 8). Post-CI word recognition tended to negatively correlate with hearing loss duration (rho = -0.6, p = 0.08, for n = 7, Figure 3B), but not with the duration of profound deafness (rho = -0.4, p = 0.2, for n = 7).

There was no significant correlation between phonological scores during the fMRI task and post-operative word recognition scores in the 7 implanted patients (rho = 0.34, p = 0.2, Figure 3C).

Functional neuroimaging results

Whole brain correlation with post-CI speech perception

We found a positive correlation between brain activation during the phonological task and post-CI word recognition scores in the left frontal, parietal and posterior temporal cortices and in bilateral occipital cortices (Figure 4, white blobs, Table 2). A negative correlation was observed in bilateral anterior temporal and inferior frontal cortices, and in the right supramarginal gyrus (Figure 4, black blobs, Table 2). When comparing levels of activation in CI candidates (split into good and poor performers) and in controls, the activated regions fell into one of four patterns (Figure 4, plots). In dorsal brain regions, neural activity for phonological processing was lower in poor than in good performers and controls. In bilateral occipital regions responses were higher in good performers than in poor performers and controls. In the whole bilateral ventral network including the anterior temporal and the inferior frontal cortices, and in the left temporo-occipital junction, responses were lower in good performers than in poor performers and controls. Finally, in the right supramarginal gyrus, responses in poor performers were higher than in good performers and controls.

Whole brain correlation with hearing loss duration

Activity in two regions correlated negatively with hearing loss duration: the left occipital and the left premotor cortices (Figure 5, yellow blobs, Table 3). These regions partly overlapped those described above as correlating positively with post-CI performance (coloured in white on Figure 5). Conversely, the single region correlating positively with hearing loss duration was located in the left inferior frontal cortex, in overlap with the ventral network associated with poor CI outcome (Figure 5, red blob over black, Table 3).

Direct group comparison

There was no brain region that was more activated in controls than in CI candidates. The only region that was over-activated in CI candidates during the phonological task was the right supramarginal gyrus (RSMG, 56 -34 26, Figure 5, green blob, p = 0.006 using Mann-Whitney, Table 3). As this region had already been identified as overactivated in deaf patients relative to controls in FDG-PET at rest (Giraud and Lee, 2007), we consider it a region of interest and thus apply an uncorrected statistical threshold. This area was not activated in controls during the rhyming task and its level of activation was independent of phonological scores (rho = 0.37, p = 0.32, Figure 5.b., squares). In CI candidates, RSMG activity correlated negatively with phonological scores (rho = -0.89, p = 0.04 for n = 6; rho = -0.88, p = 0.02 for n = 8, Figure 5.b, circles) and showed a weak trend to increase with both deafness duration and hearing loss duration (at 56 -34 26, rho = 0.67, p = 0.1 for n = 6 and rho = 0.65, p = 0.09 for n = 8 for deafness duration, and rho = 0.77, p = 0.08 for n = 6, and rho = 0.6, p = 0.1 for n = 8 for hearing loss duration). Importantly, there was a negative correlation between brain activity in the RSMG (at 58 –40 32) and post-CI word recognition scores in a region that was also more activated in CI candidates than in controls. This negative correlation (rho = -0.98, p

= 0.03 for the 6 first CI candidates, Figure 5.b) also held when including in *post-hoc* non-parametric tests patient 8 who received an implant after 360 months of profound deafness with residual hearing (rho = -0.77, p = 0.06). The contrast phonological *versus* semantic task in CI candidates relative to controls confirmed that RSMG overactivation was specific to phonological processing (at 62 -40 18, cluster size 32, p=0.002, Z=2.90).

Whole brain fMRI correlation with pre-CI phonological scores

No other brain region than the RSMG correlated negatively with phonological scores. Activity in the left prefrontal cortex that covaried negatively with hearing loss duration covaried positively with phonological scores (Figure 5.a, circles). Activation levels in the premotor cortex were about equal in CI candidates and controls, suggesting a physiological use of this area in phonological tasks. In *post-hoc* non-parametric tests, this effect only held for those CI candidates without residual word recognition ability (rho = 0.94, p = 0.03 for n = 6, Figure 5.a). CI candidates 7 and 8 with residual hearing behaved as outliers showing activation levels higher than both normal-hearing subjects and the others.

DISCUSSION

Limits to a behaviourally informed clinical approach

It is widely admitted that CI success depends on auditory deprivation duration: the shorter, the better (Blamey et al., 1996; Green et al., 2007; Proops et al., 1999; van Dijk et al., 1999). In post-lingually deaf subjects, however, this dependency is less marked and less reliable than in the prelingually deaf. We confirm here that speech perception with a CI is rather loosely related to the duration of auditory deprivation in post-lingually deaf subjects, even if we take into account the whole history of hearing loss that better reflects progressive cortical reorganization than the time elapsed since total deafness. The current data show that CI prognosis could fruitfully be informed by assessing the neural strategies that accompany brain plasticity during deafness, and by probing their relevance for word perception after cochlear implantation.

Progressive degradation of hearing in post-lingually deaf subjects enforces the use of speechreading and thus strengthens audio-visual interactions during phonological processing (Doucet et al., 2006; Lee et al., 2007b). When hearing can no longer help to disambiguate visemes, visual speech alone becomes ambiguous, and phonological representations degrade and loose their accuracy by lack of auditory reinforcement (Andersson et al., 2001). Restoring hearing with a CI promotes a new sound-to-phoneme matching and in parallel restores viseme-to-phoneme correspondence (Doucet et al., 2006; Giraud et al., 2001). One could deduce from these observations that residual accuracy of phonological representations is advantageous for audio-visuo-phonological matching with a CI. Such a mechanism would indicate that these representations serve as internal models to structure the continuous incoming signal. Yet, sounds provided by an implant differ markedly from physiological hearing and it might as well be the case that it is important to not have too strong phonological templates to allow for more flexibility in new sound-to-viseme matching.

The current behavioural data only weakly support the idea that pre-CI phonological processing determines CI outcome (weak non-significant positive correlation between pre-CI rhyming and post-CI speech performance). However, as only 8 CI candidates were included in a task that was purposely kept easy, we cannot conclude on this issue. More difficult phonological tests would have to be used to assess whether a simple visual rhyming task could effectively predict CI outcome. Yet, by relating post-CI word recognition scores to pre-CI fMRI data during this simple rhyming task, we could identify distinct modes of neural adaptation to deafness that are individually more relevant to CI success than pre-CI clinical/behavioural parameters.

Dual phonological strategy predicts opposite CI outcomes

In normal hearing adults, phonological processing can be accessed from either the auditory or the visual modality (*Schorr et al., PNAS 2005*), and in the latter case from facial movements and from written language material (Sekiyama et al., 2003; von Kriegstein and Giraud, 2006; Woodhouse et al., 2008). In post-lingually deaf people, audio-visual speech processing is compromised, yet phonological representations should be mobilized in the context of reading. As the absence of auditory reinforcement is accompanied by a decrease in phonological accuracy (Andersson et al., 2001), the brain system involved in reading is presumably affected.

In agreement with the dual route theory of reading, we found that phonological processing from written regular material involved dorsal brain regions in controls (supplemental Figure 1). Future good CI performers also used the dorsal route, and additionally recruited occipito-temporal regions, a strategy that was not used by future poor CI performers. Our data suggest that future good performers used visual inputs and performed viseme-to-phoneme matching, which likely denotes an enhanced propensity to maintain oral communication and audio-visual speech processing (Doucet et al., 2006; Giraud and Truy, 2002; Rouger et al., 2007). Likewise, the phonological task involved left prefrontal and parietal regions in controls and good CI performers, reflecting a similar degree of orthographic–to-phonologic mapping in both groups (Booth et al., 2006). That activity in both visual and prefrontal regions negatively correlated with hearing loss duration, supports our hypothesis that phonological processing decays with deafness, and that post-lingually deaf subjects may resort to this strategy only at the beginning of the deafening process, when phonological representations are still accurate.

Poor CI performers did not rely on the dorsal route and visual processing to perform the rhyming task, but activated anterior and ventral networks. This suggests that future poor performers resort to a global semantic approach to written material even if the reading task places specific demands on phonological processing. Activity in the anterior part of the inferior frontal gyrus, involved in semantic access (Vigneau et al., 2006), correlated positively with hearing loss duration. This observation suggests that poor performers turn to the semantic “global” route to palliate progressive phonological decay. In sum, what appears to be an adaptive strategy to compensate for a phonological deficit during deafness turns out to be a handicap in the context of auditory rehabilitation. Once the direct route becomes predominant during deafness, patients will encounter difficulties in matching CI sounds to stored phonological representations.

Those prelingual deaf adults who develop good reading skills are generally able to make correct rhyme judgments (Aparicio et al., 2007; MacSweeney et al., 2009). In these subjects, reading involves a dorsal network that is not as well developed as in controls and less left-lateralized (Aparicio et al., 2007; MacSweeney et al., 2009; Neville et al., 1998). This altered network denotes the use of expressive (articulation and inner speech) phonology rather than auditory and orthographic matching skills (Aparicio et al., 2007; MacSweeney et al., 2009). Likewise, it is not excluded that post-lingual good CI performers resort more than poor performers to inner articulation.

These data provide a neurophysiological framework for proposing that there are two populations of post-lingually deaf adults, “readers” and “lip-readers”. Readers probably abandon oral communication and phonological processing to essentially communicate through written language using global word recognition. Conversely, lip-readers continue to rely on phonological representations through enhanced visual speech processing, and thus maintain the indirect route, a strategy that is essential for segmenting speech flow in phonological units (Giraud and Lee, 2007).

Hearing loss duration is probably one factor that determines the shift from one strategy to the other. Once phonological representations become too inaccurate to maintain a viseme-phoneme matching, post-lingually deaf subjects switch to a more efficient alternative. As there was only a partial overlap between areas showing a correlation with hearing loss duration and those showing a correlation with CI outcome (Figure 5), predominance of either strategy might ultimately depend on individual preferences for oral or written language. It has previously been suggested that reading should be encouraged in CI candidates (Giraud et al., 2001; Rouger et al., 2007). Yet, the current findings show that reading may sometimes induce detrimental cognitive strategies. We propose here that reading strategy might be used for guiding specific rehabilitation in CI candidates at risk.

Involvement of the right SMG

A single region of the right supramarginal gyrus was overactivated in CI candidates relative to controls. This region also negatively correlated with pre-operative phonological scores and with post-CI word recognition scores, and exhibited only a weak positive correlation with hearing loss duration. In FDG-PET in both congenitally deaf children and in post-lingually deaf adults (Giraud and Lee, 2007), this same region correlated negatively with post-CI speech scores even when the impact of deafness duration was factored out. The current results thus confirm that neural activity in this region predicts poor CI performance, and show that it is involved in written language processing during deafness. As its recruitment does not depend on hearing loss duration, it may point to neural plasticity that occurs very early in the course of hearing loss. Phonological difficulties encountered at the beginning of deafness might rapidly prompt compensation for a deficit in the access to the phonological route (Aparicio et al., 2007) by contralateral regions (Jacquemot et al., 2003). As the right SMG is normally involved in other cognitive tasks than phonological processing, e.g. processing of non-linguistic acoustic, pitch, etc. (Rimol et al., 2005; Thierry et al., 2003; Toyomura et al., 2007), its recruitment could ultimately be detrimental to post-CI speech processing (Hillis, 2006). Deleterious effects of contralateral compensation have been shown in several other clinical conditions as aphasia and stuttering (Marsh and Hillis, 2006; Martin and Ayala, 2004; Naeser et al., 2005; Preibisch et al., 2003). Even though the neurophysiological mechanism underlying a correlation between right SMG activity and poor performance after CI are unknown, it appears a reliable marker of a bad CI prognosis across several neuroimaging studies.

Variability in deafness history and functional prognosis

The case of Patient 8 is interesting as he had been deaf for an extremely long duration, while exhibiting residual speech perception and good phonological performances when he received his implant. Surprisingly, he had very low word recognition scores after cochlear implantation. He thus does not follow our hypothesis that pre-CI phonology skills should commensurate with the outcome. From a functional viewpoint this CI candidate appeared as an extreme case of indirect route use for reading with very high activity levels in the left prefrontal region. As shown in Supplemental Figure 2, he strongly relied on the dorsal route to perform the phonological task. This profile suggests that a CI candidate who has trained too long to grasp small phonological details might finally be at a disadvantage when matching new sounds with residual and probably very degraded phonological representations. An alternative account for his poor post-CI performance could be that the limitation is downstream, i.e., that on-line phonological processing succeeds at the expense of semantic integration. Overall, CI success seems to rely on preserving a phonological store and phonological circuits in a state that is not too reorganised to permit upstream and downstream processing, *i.e.* contact with new sounds through acoustic processing and contact with sound meaning through semantic access.

CONCLUSION

We identified two neurofunctional traits that prospectively distinguish good and poor CI performers based on their approach to written language. While the maintenance of *normal* “dorsal” phonological circuits in the course of deafness predicts a good outcome, the switch to an alternative lexico-semantic “ventral” route and the recruitment of the right supramarginal gyrus to compensate for deficient phonological processing suggests a poor outcome. Although a systematic fMRI investigation of language function might not be conceivable in clinical routine, the current data suggest that carefully examining the phonological “dorsal” versus ventral” strategies, *e.g.* by measuring reading velocity using tasks on regular and irregular words, pseudowords and orthographically illegal words, could be used in the future to detect phonological withdrawal and refer deaf CI candidates at risk to adapted pre-CI training and post-CI rehabilitation.

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Annex 1: Example of words of the Lafon‘s list

1	**2**	**3**	**4**	**5**
buée	bile	rôde	abbé	balle
ride	dors	fente	sud	soude
foc	sage	tige	fausse	mur
agis	gaine	grain	joute	nef
vague	fil	cave	dogue	change
croc	cru	bulle	acquis	gage
lobe	boule	somme	ville	trou
mieux	cale	maine	mare	mal
natte	bonne	preux	noce	tonne
col	rive	bord	appas	peur
fort	sol	rouille	route	rampe
soupe	tempe	oser	cil	puce
tonte	fauve	site	fête	cor
vêle	phase	bouée	veule	vite
nage	mule	sauve	chaise	rance
souche	chatte	chance	bâche	mouche
rogne	règne	gagne	souille	fille

Figure legends:

Figure 1: Experimental paradigm. *fMRI* data were acquired prior to the cochlear implantation. Six months after implantation, word recognition scores were collected. Imaging data were correlated with behavioural and clinical data.

Figure 2: Behavioral results during fMRI rhyming phonological tasks A. Performance, B. Reaction times. CI candidates and controls did not differ in either parameter.

Figure 3: Correlations between clinical and behavioural data. A. 6 months postoperative word recognition scores as a function of hearing loss duration, B. Phonological scores during fMRI experiment as a function of hearing loss duration, and C. as a function of postoperative word recognition scores. 7 CI candidates were implanted (1 to 6 and 8).

Figure 4: Surface rendering of correlation between speech recognition scores 6 months after cochlear implantation and fMRI data. Effect displayed at p=0.005 (T = 4.60). Positive correlation: white blobs. Negative correlation: black blobs. The contrast estimates changes illustrate four different recruitment patterns in poor -performers (black circles), good performers (open circles) and controls (squares).

Figure 5: Correlation between hearing loss duration and fMRI data. Effect displayed at p=0.001 (T = 3.86), for positive and negative correlation (red and yellow blobs) and at p=0.001 (T = 3.78), for CI candidates more than controls during phonological tasks (green blob). Results from Figure 4 are overlaid.

a. Neural activity in the left prefrontal cortex appeared to be the same in CI candidates and controls but positively correlated with phonological scores in the first 6 CI candidates only.

b. Activation in the right supramarginal gyrus (at 56 –34 26) negatively correlated with phonological scores in CI candidates (black circles) but not in controls (grey squares). Neural activity (at 58 –40 32) negatively correlated with post-CI speech recognition scores in implanted subjects (p=0.06 in the 7 implanted subjects and p=0.03 in the first 6 subjects).

Supplemental data legends: Effects displayed at p = 0. 01 (T=3.11).

Figure 1: Group analysis of the contrast phonological task versus baseline in control subjects.

Figure 2: Single subject analysis of the contrast phonological task versus baseline in Patient 8.