## Role of audiovisual plasticity in speech recovery after adult cochlear implantation

Pascal Barone<sup>1</sup>, Kuzma Strelnikov<sup>1</sup>, Olivier Déguine<sup>1,2</sup>

1. Cerveau & Cognition UMR 5549, 2. Service d'Oto-Rhino-Laryngologie, Hopital Purpan, Toulouse France

barone@cerco.ups-tlse.fr

## Abstract

The role of vision on the speech recovery after cochlear implantation is a subject of debate. In our study, we assessed the role of crossmodal reorganization and plasticity in auditory recovery in cochlear implanted deaf patients. Our results demonstrate that the initial functional level of the visual cortex leads to the greater proficiency in auditory recovery. Experienced patients had greater activity in the left middle temporal cortex known for audiovisual integration. The time course of temporal and visual activity in experienced patients was highly correlated meaning their synchronized integrative activity. Our data confirms the importance of visual activity and audiovisual integration in speech comprehension in cochlear implanted subjects by establishing the neural underpinnings for this integration.

Index Terms: cochlear implantation, speech, vision

## 1. Introduction

Modern cochlear implantation (CI) technologies allow postlingual deaf patients to understand auditory speech through longterm adaptive processes that lead to coherent percepts from the coarse auditory input delivered by the implant. During the period of deafness, subjects maintain oral comprehension by developing lip reading. After implantation, the use of lip reading does not decrease because the crude information transmitted by the CI requires the persistent use of visual cues, especially in noisy situations [1]. Due to the complementary nature of the visual and the auditory information, during progressive hearing recovery, the capacities of the patients for speech intelligibility rely principally on the visual and visuo-auditory processing of speech [1, 2]. However, in postlingual CI patients, vision can be deleterious for non-speech [3, 4] or during incongruent or ambiguous audiovisual conditions [5]. In this article, we posed the question whether initial visual activity of the brain has a positive or negative impact on speech perception of cochlear implanted patients. Besides, we asked whether visual and auditory activities are modified with experience postimplantation.

#### 2. Materials and methods

## 2.1. Subjects

10 deaf cochlear implant patients (CI) and 6 normally-hearing (NH) subjects were involved in this PET neuroimaging study. Participants of both groups were native French speakers with self-reported normal or corrected-to-normal vision and without any previously known language or cognitive disorders. All CI patients had postlingually acquired profound bilateral deafness (defined as a bilateral hearing loss above 90 dB) of diverse etiologies and durations. The clinical implantation criteria included word and open-set sentence auditory-recognition scores below 30% under best-aided conditions (i.e. with conventional acoustic hearing aids). CI patients were recipients of a unilateral cochlear implant (5 on the left side and 5 on the right side) respectively. Cochlear implants were completely inserted in the scala tympani, allowing an optimal activation of stimulating electrodes. The group of patients included 7 women and 3 men aged between 35 and 81 years (mean 53.9 years), while the normally-hearing group included 6 men aged between 20 and 49 years (mean 34.2 years). All participants gave their full-informed consent prior to their inclusion in this study, in accordance with local ethics committees (Toulouse, France).

## 2.2. Stimuli

Stimuli were French bisyllabic words (e.g. /sitrõ/, english *lemon*) and meaningless temporally-reversed bisyllabic words (non-words). Words and non-words were pooled into lists of 40 stimuli each, including 20 words and 20 non-words in random order.

#### 2.3. Stimulation conditions

During Rest, subjects lied in the camera eyes closed without any auditory stimulation. The Motor control condition consisted in presenting the photos of the speech therapist in the correct or upside-down position, the subject was to indicate the correct or uncorrect position of the picture with mouse buttons; this condition was used to exclude motor activities and the nonspecific to speech visual processing. Visual speech condition was speechreading: words and non-words were presented in the visual modality without any auditory stimulation. Audiovisual speech condition consisted in presenting videos with sound. In Visual and Audiovisual speech conditions, subjects had to identify whether they recognized or not the words using a twobutton computer mouse with their right hand.

Due to the restrictions on the level of radioactivity load during the PET experiment, we decided that the audiovisual condition would be better than the auditory-only one. We think that this condition is more ecological and especially it is easier to perform by the patients just after the implantation.

#### 2.4. Positron emission tomography

Subjects were scanned in a shielded darkened room with their head immobilized and transaxially aligned along the orbitomeatal line with a laser beam, with position controlled before each acquisition. Measurements of regional distribution of radioactivity were performed with an ECAT HR+ (Siemens<sup>®</sup>) PET camera with full volume acquisition (63 planes, thickness 2.4 mm, axial field-of-view 158 mm, in-plane resolution  $\approx 4.2$  mm). The duration of each scan was 80 s; about 6 mCi of H<sub>2</sub>O<sup>15</sup> was administered to each subject for each individual scan.

There were two runs per each condition, 3 images were acquired during each run, 8 runs resulted in 24 images per subject.

Stimulation on the experimental conditions was started  $\approx 20$  s before data acquisition and continued until scan completion. Experiment instructions were given to subjects before each tomography and repeated before each run.

### 2.5. Data analysis

# 2.5.1. Impact of the initial visual activity on speech recovery

Neuroimaging data were analyzed with SPM, including the standard procedures of image pre-processing (realignment, spatial normalization, smoothing with 8 mm Gaussian kernel), defining the models and their statistical assessment. In order to search for the relationship between brain activity and auditory recovery we conducted two complementary analyses on noncontrasted activity maps. Firstly, we performed a regression analysis to detect brain areas whose activity level correlated with the word recognition score that had been collected by the speech therapist and obtained 6 months after the PET scan session. The ensuing images were estimated in the whole brain analysis using voxel-level t- and z- values, which corresponded to p < 0.05 with a family-wise error correction for multiple non-independent comparisons. In each patient, a sphere with 4 mm radius (corresponding to the used smoothing of 8 mm) was placed on the peak issued from the whole brain group analysis (see above). Then the mean activity was calculated in this sphere in individual patients. Lastly, the mean relative difference between the value from the sphere and the global activity value was calculated per subject and correlated with the scores obtained at 6 months.

Our strategy to assess patients at 6 months is based on our previous data obtained on a large cohort of CI patients [1]. At 6 months, most of the patients already reach an optimal performance level in auditory speech recovery. Thus, 6 months is a key period, which is reasonable for longitudinal measurements.

### 2.5.2. Modification of brain activity by CI experience

Neuroimaging data were first analyzed with SPM software including the standard procedures for images pre-processing (realignment, spatial normalization to the Montreal Neurological Institute brain template, smoothing with 8 mm isotropic Gaussian kernel), models definition and statistical assessment.

Two types of SPM design matrix were constructed. One type was for group comparison and comprised groups of subjects as regressors: NH, T0 (neousers patients, mean CI experience 7 days) and T1 (experienced patients, mean CI experience 7 months). Such a matrix was constructed separately for the images from the Visual and Audiovisual conditions. Another SPM design matrix was used for within-group analysis and comprised 4 regressors corresponding to 4 conditions of the study. Such a matrix was constructed separately for the NH, T0 and T1 groups of subjects. The SPM matrices were used to set regressors for the images entered into the independent components analysis (ICA).

The independent components analysis was realized with the Group ICA toolbox GIFT (http://mialab.mrn.org/software/) in Matlab. The Fast ICA stabilized algorithm was used, the number of independent components was taken equal to the number of

images per subject in within-group analysis or per-group in between-group analysis, with regular back reconstruction and zscores as scaling components. Multiple regression of activity in the extracted components with regressors from the SPM design matrix were assessed using the  $r^2$  value at p<0.01.

As we were interested in the sensory components of audiovisual interaction, we selected the components where the maximum of activity was in the occipital and temporal regions. For example, some motor components emerged from the ICA due to the motor control task; we excluded these regions from our study as it is out of the scope of the present speech study.

## 3. Results

## 3.1.1. Impact of the initial visual activity on speech recovery

The whole brain regression analysis revealed that the activity in the right occipital visual cortex immediately post-implantation was significantly related to the auditory scores at about 6 months (Figure 1).

### **Resting condition**



Figure 1. Correlation between the initial occitital activity and auditory scores 6 months post-implantation. Overlap between the conditions.

This positive significant correlation was obtained in the three brain imaging conditions: resting state, visual speechreading and audiovisual word discrimination. As we had an *a priori* hypothesis about occipital activity, we applied the correlation analysis on an individual basis with spheres at the peaks of the most significant clusters for each condition. This analysis resulted in impressively high correlation values. Indeed, the correlation level (r values) between the activity level in the right occipital cortex and the auditory scores were 0.9 for the resting condition, 0.8 for the visual speechreading, and 0.5 for the audiovisual condition.

In all cases, the correlated clusters in the occipital region corresponded mainly to the extrastriate visual cortex (BA18) but they partly involved the primary visual cortex. According to the probabilistic cytoarchitectonic maps [6], in the resting condition, the occipital cluster has a 40% probability of being located in BA 17 and an 80% probability of being located in BA 18. Similarly, in the visual condition the cluster has a 50% probability of being located in BA 17 and a 90% probability of being located in BA 18. Lastly, in the audiovisual condition, the probability that the occipital cluster will be located in BA 17 is 50% and there is a 90% it will be located in BA 18. Considering the Euclidean distances between the peaks, we did not find a difference between the visual and audiovisual conditions. Both peaks in the visual and audio-visual conditions were located 2 mm apart from the peak at rest, which felt within the smoothing precision of 8 mm.

By looking at the overlapping surface and the Euclidian distances between peaks of activity we showed that the spatial extent of the right occipital cluster in the visual condition had a 76% overlap with that obtained in the at rest condition, and at 53% with that obtained in the audiovisual condition (Figure 1). The overlap between the right occipital clusters during the visual and audiovisual stimulations was 47%. All together, the anatomical localization studies suggest that the 3 occipital clusters, which are correlated with the values of auditory recovery, represent the same visual cortical region that includes mainly BA18.

No correlation in the reported areas was detected with auditory scores initially after implant activation (p>0.8) meaning that the observed predictive correlation does not reflect the initial performance of the patients.

### 3.1.2. Modification of brain activity by CI experience

Firstly, we wanted to check whether there was a difference between the groups of normal subjects and patients at the early (T0) and late (T1) stages post-implantation. The between-group analysis was performed for each stimulation condition and rest. As a result, in the between-group analysis, the only difference was observed for the Audiovisual condition, the component having maximum in the left middle temporal region (-60, -10, -2),  $r^2=0.65$  (Figure 2).



Figure 2. Higher activity at T1 compared to T1 and controls in audiovisual condition.

To confirm the group effect in this condition, we performed the ANOVA analysis of activity at the peak of the detected component. ANOVA revealed significant between-group differences (p<0.0001, F (2,135)=130.79). It is important that there was no significant difference between NH and T0 (p=0.96) but the difference was significant between NH and T1 (p<0.0001) as well as between T0 and T1 (p<0.0001). It means that the global between-group effect is caused by the activity at T1, which is different both from controls and from T0.

Having established the differential activity between the groups, we proceeded with the analysis within each group (NH controls, T0, T1). For each group, we searched for the components correlated with the sequence of the stimulation conditions (Rest, Motor control, Visual speech and Audiovisual speech). In the within-group analysis, components of interest correlated with condition were found for T0 and T1 groups of patients, no significant components were observed in controls.

In T0 group, the component was observed bilaterally in the occipital region with a maximum in the left middle occipital visual region covering BA17/18/19 (Figure 3) and a sub-maximum in the right middle occipital region (16, -102, 12),  $r^2=0.86$  with a similar spread.



Figure 3. Occipital activity affected by the condition factor at T0 and T1.

To test the effect of condition on the peak of this component, the ANOVA comparison was applied. The ANOVA analysis yielded significant difference between the 4 conditions in this component (p<0.0001, F (3, 212)=120.47).

In T1 group, one component had maximum in the left middle temporal region (-62, -12, -2),  $r^2=0.65$  covering BA22/21/37 (Figure 4A).



Figure 4. A. Temporal activity affected by the condition factor at T1. B. Correlation between temporal and occipital activities at T1.

The other component had bilateral distribution with a maximum in the left lingual region (-28,-98,-10) and a sub-maximum in the right occipital inferior region (24,-96,-4),  $r^2$ =0.50 both covering BA17/18/19 (Figure 3). ANOVA comparison of activity during the conditions yielded significant difference both in the left temporal region (p<0.0001, F (3, 188)=29.7) and in the left lingual region (p<0.0001, F (3, 188)=38.7). The overlap of the occipital clusters between T1 and T0 was 0.9 with respect to T1. The Euclidian distance between the peaks of these clusters was 10 mm. Thus, there is a high spatial overlap between the temporal clusters. The overlap between the left temporal cluster in T1 and the left temporal cluster in the group effect for the audiovisual condition was 0.5 with respect to T1. The Euclidian distance between the peaks of these clusters was less than 3 mm being within the smoothing of 8 mm. Thus, there is a high coincidence of peaks for the occipital clusters.

To assess whether the two components observed at T1 correlated in the same way with condition, we performed a correlation between these components taking activity at the peak in the left middle temporal and left lingual regions. This correlation was 0.92, p<0.001 meaning that the two components varied with the task in the similar way (Figure 4B).

Given the correlation with condition in the left temporal region at T1, we posed a question whether activity in this region can be related to the behavioural scores in the visual and audiovisual conditions and thus reflect the difference in performance between these conditions. We included both visual and audiovisual speech recognition scores into the correlation with the peak activity in the left temporal cluster. This correlation was 0.57, p<0.02. It can be explained by the fact that during visual task activity in this area was significantly smaller than during audiovisual task (p<0.01) reflecting the same difference in behavioural scores between the tasks (p<0.01). Thus, activity in this area varies in the same direction as behavioural scores during visual and audiovisual speech perception.

## 4. Discussion

## 4.1.1. Impact of the initial visual activity on speech recovery

In the present study, using three different conditions (visual, audio-visual word discrimination and rest) the same visual region presents a positive correlation with CI outcomes. Consequently, the predictive role of the occipital visual cortex is task and modality-independent, which reinforces its role for long-term adaptive strategies. The higher the level of activity in the visual cortex, the higher the auditory proficiency will be after cochlear implantation. This visual region corresponds to the representation of the central visual field (about  $3^\circ$ ), which suggests an implication in foveal gazing, such as during lipreading.

The beneficial commitment of the visual cortex for auditory recuperation after cochlear implantation corresponds to the important role of visual input for speech comprehension in postlingual deaf patients [1, 7-9] concerning both phonological and lexical access. During the partial restoration of audition by cochlear implants, the visual counterpart of the audiovisual objects helps decipher the auditory information and finally increases the capacities for auditory discrimination [2]. Such visuo-auditory synergy is also observed at the neurofunctional level in CI users, in which, after implantation, there is a progressive increase of activation in the visual areas [8, 10]. Similarly, in normal-hearing subjects there are evidences at a neuronal level of the facilitatory visual influence on auditory response s[11-13]. One can suggest that such mechanisms can be more efficient in CI users with a high initial level of activity in the visual cortex after implantation leading to higher proficiency in auditory recovery.

### 4.1.2. Modification of brain activity by CI experience

Using ICA in between-group analysis, we showed that experienced patients had greater activity in the left middle

temporal cortex compared with inexperienced ones and controls. In within group analysis of experienced patients, a spatially independent task-related component was observed in the left middle temporal cortex as well. Patients in both groups had a task-related component in the visual cortex. The time courses (changes of activity between the conditions) of temporal and visual activity in experienced patients were highly coupled. This coupling suggests that visuo-auditory synergy is crucial to adjust cross-modal plasticity, which is necessary for the recovery of speech comprehension in adult cochlear implanted deaf patients.

## Occipital and temporal activity in CI patients

Both at T0 and at T1 (Figure 3) the independent component involved the occipital cortex with similar localizations in the BA17/18/19, which include the representation of the foveal gaze [14]. This component is likely functionally related to the specific oculomotor strategy developed by deaf subject for speechreading. At time of implantation, and following a long period of deafness, CI patients have developed high skills in speechreading that overpass that observed in normal hearing subjects. While some studies reported only mild improvement in speechreading performances after cochlear implantation [15, 16], there is strong evidence that such strategy is maintained across time in spite of the auditory recovery [1, 10]. One reason for preserving the high speech-reading ability is that it contributes to bi-sensory integration which improves speech recognition in noisy environments, a challenge for the majority of CI recipients.

An important finding is that in addition to the occipital components, the component in the left temporal cortex turns out to be specific to T1 patients both in the between-group (Figure 2) and within-group (Figure 4) analyses. The peaks of the clusters are situated in a region shown to be more active in audiovisual speech than in separate auditory and visual conditions [17]. Further, this cortical region is also specifically activated during matching of auditory and visual stimuli in verbal conceptual processing [18, 19]. Thus, its role consists in mapping the auditory and visual speech information providing the integrative audiovisual concept. Hence, we hypothesize that the higher activity in the temporal cortex in CI patients at T1 reflects the supranormal audiovisual speech processing described in these patients [1, 2].

The crucial finding in our study concerns the strong correlation observed between the temporal and visual cortices related to the experience with cochlear implant. This positive correlation suggests that there is a functional coupling that involves visual and visuo-auditory integration of speech. This coupling is progressive as long as the patients are experiencing the implant because in the first months post-implantation the patients rely more strongly on the visual modality. We propose that the functional coupling revealed in the present, which concerns the visual occipital and visuo-auditory temporal regions, reflects at the neuronal level the compelling visuo-auditory synergy on which is based the recovery of speech comprehension in CI patients.

Thus, our results on the temporal and occipital activity at T1 emphasize the increased cross-modal interplay in the experienced CI patients, which is consistent with the cross-modal activations of low-level visual areas during auditory-only speech perception in CI patients [10].

## 5. Conclusions

In postlingual CI deaf patients, the influence of the visual cortex on the efficiency of purely auditory speech perception suggests the existence of some neural facilitation mechanisms that build up a real synergy between the two modalities, so that a better functional level of one modality leads to the better performance of the other [2]. Such cooperation may be a reflection of the multisensory nature of the perceived world, a feature which is especially present in speech.

The present data establishes the neural underpinnings of high audiovisual integration in experienced cochlear implanted subjects by demonstrating the existence of the specific brain network of audiovisual integration in this group of patients.

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