Cognitive Reconstruction of Reversed Speech in French

Claire Grataloup (claire.grataloup@etu.univ-lyon2.fr)
Michel Hoen (hoen@isc.cnrs.fr)
Fanny Meunier (fanny.meunier@univ-lyon2.fr)
& Francois Pellegrino (françois.pellegrino@univ-lyon2.fr)
Laboratoire Dynamique du Langage. UMR 5596 CNRS - Université Lyon2.
Institut des Sciences de l'Homme. Lyon - FRANCE

Evelyne Veuillet (evelyne.veuillet@chu-lyon.fr)
& Lionel Collet (lionel.collet@chu-lyon.fr)
Neurosciences & Systèmes Sensoriels. UMR 5020. CNRS - Université Claude Bernard Lyon 1
Lyon - FRANCE

Abstract

In the present study we explore the implication of high and low level mechanisms in degraded (time-reversed) speech comprehension in normal hearing subjects. In experiment 1 we compared the loss of intelligibility due to the increasing size of reversion windows in both words and pseudowords. Results showed that words are generally reconstructed better than pseudowords, suggesting the existence of a lexical benefit in degraded speech restoration. Moreover, there was greater variability between individuals when reconstructing pseudowords than words. In experiment 2, we demonstrated that this interindividual variability correlated with the subjects' medial olivocochlear bundle functionality. These experiments highlight the importance of low-level auditory mechanisms in degraded speech restoration. In a third experiment, we performed ERP recordings during an auditory sentence comprehension task in which sentences could contain partially reversed words. Results suggest that both an automatic auditory violation detection component, the mismatch negativity (MMN), and a subsequent negative frontal wave (N600) were present. Moreover, only this later wave was modulated by the size of the reversion. Together, these results put forward the existence of major interindividual variability in the capacity to reconstruct degraded speech, which correlates with the physiological properties of the auditory system. In addition, our results also suggest the existence of multiple higher-level strategies that can compensate on-line for the lack of information caused by speech degradation.

Keywords: Auditory ERP, High and low levels processes, Intelligibility, Medial OlivoCochlear Bundle, Reversed speech.

Introduction

Understanding speech is fast and automatic; this process is a daily task achieved without any difficulty although it involves cognitive functions which are both numerous and complex. The intelligibility of speech depends both on the quality of the emitted signal and on the ability of the cognitive system to process this signal. To understand spoken messages requires the complementary engagement of low-level (auditory) and high-level mechanisms (e.g., lexical knowledge, contextual integration).

At the sensory level, the human auditory system may be described throw two types of pathway: "ascending" and "descending" auditory pathways. Ascending pathways carry the auditory message from receptive hair cells in the cochlea to the primary auditory cortex. Descending pathways extending from the auditory cortex to the periphery through the superior olivary complex constitute a sort of inhibitory filter (Khalfa & Collet, 1996) which may play a role in degraded speech comprehension. The existence of a central influence on the sensory level by means of efferent feedback pathways has been highlighted with the investigation of the medial olivocochlear bundle (MOCB). It is possible to explore the MOCB in a simple and non invasive way through contralateral suppression of otoacoustic emissions (OAEs), sounds produced by the outer hair cells of the cochlea (Collet, Kemp, Veuillet, Duclaux, Moulin & Morgnon, 1990). Important interindividual variability in normal hearing subjects was also observed by the same authors when assessing the functionality of the MOCB. Though the precise functional role of the MOCB remains unclear, several studies have suggested its involvement in speech intelligibility in degraded conditions. A correlation between the functionality of MOCB and the detection threshold of pure tones present in noise was first reported by Micheyl and Collet (1996). Giraud, Garnier, Micheyl, Lina, Chays and Chéry-Croze (1997), also reported that MOCB activation via contralateral noise stimulation improved speech-in-noise intelligibility in normal hearing subjects. More recently Kumar and Vanaja (2004) suggested a correlation between the contralateral suppression of evoked OAEs and speech identification scores at certain signal/noise ratios.

However speech comprehension is likely to benefit during auditory sentence comprehension from higher level knowledge such as lexical knowledge stored in the mental lexicon or contextual information. Interactive theories of speech perception postulate that several sources interact during perceptual analysis (McClelland & Elman, 1986).

The aim of our study was to characterize involvement of high and low-level processes during the comprehension of speech in degraded conditions. To study these mechanisms we manipulated the intelligibility of speech signals by applying temporal reversions on different-sized windows (i.e., flipping the signal on its horizontal axis). Reversed speech has the particularity that it maintains the physical characteristics of speech such as the distribution frequency of sounds, their global amplitude and, to some extent, their temporal and rhythmic characteristics. The main difference between speech and reversed speech lies in the coarticulations which are totally distorted in the reversed signal. Thus, reversed speech is unpronounceable though to some extent it remains understandable. Saberi and Perrott (1999) demonstrated that it is possible to reconstruct locally reversed English speech (for comparable results see Greenberg & Araï, 2001 and Meunier, Cenier, Barkat & Magrin-Chagnolleau, 2002, for results on French). All these studies applied time reversions according to arbitrarily augmenting time-windows (20 ms, 40 ms, 60 ms…). For the present work, time reversions were based on the syllable unit as it has been identified as a privileged unit for lexical access in French (Content, Dumay & Frauenfelder, 2000). In experiment 1, we measured the accuracy in restoring single words and pseudowords to quantify the lexical effects during this process. In experiment 2 auditory measurements were made to test the implication of auditory pathways in the reconstruction phenomenon. Finally we completed our results with electrophysiological measurements to characterize the implication of high-level processes.

Experiment 1: Behavioural measures

Materials and methods

Stimuli Word stimuli consisted of 120 French nouns. All were common disyllabic words. They were selected according to two main criteria: their frequency (High or Low) and their number of phonological neighbours (Many or Few). (*Lexique* database, New, Palier, Ferrand & Matos, 2001). For example the word */ballon/ (balloon)* is a high frequency noun (f=4.39) that has many phonological neighbours (20) (*e.g., /vallon/*, */baron/*, */baton/*…). We crossed Frequency and Neighbour factors in order to create 4 categories of 30 experimental nouns each. For each category Table 1 gives the mean and the standard deviation of each factor (frequency and number of phonological neighbours).

Table 1: The four categories of experimental words.

Category	Frequency (log2)	Neighbours
Low-Few	m=0.51; SD=0.87	m=3.79; SD=1.96
Low-Many	m= 1.16; SD=1.2	m= 17.73; SD=4.12
High-Few	m= 4.4; SD=1.53	m=3.63; SD=1.87
High-Many	m=4.65; SD=1.51	m=19.37; SD=5.66

We also constructed 120 experimental disyllabic pseudowords (e.g.: *lantin*) using the same syllables contained in the 120 experimental words. These pseudowords satisfied the constraints observed in French phonotactics. All 240 items were recorded in a soundproof room by a native French speaker. We applied five kinds of reversion to the items:

- Condition R_0: no reversion applied.
- Condition $R_{0.5}$: first half syllable reversed.
- Condition R_1: first syllable reversed.
- Condition $R_{1.5}$: first syllable and a half reversed.
- Condition R_2: whole item reversed.

The half syllable was defined as the half in terms of the duration of a syllable.

Experimental procedure Participants faced a computer screen (PC type) and heard the stimuli delivered binaurally via headphones. The presentation order of the 240 stimuli was randomized across subjects. The participants had to type on a computer keyboard what they had understood.

Participants 50 native French speakers aged between 18 and 25 participated in this study. None had any auditory problems.

Results

Results were obtained by comparing the subjects' transcriptions to the original words or pseudowords. Taken as a whole, the percentage of intelligibility decreased with increasing distortion. The average reconstruction score was 97.3% for condition R_0; 79.65% for $R_{0.5}$; 51.15% for R_1; 2.85% for $R_{1.5}$ and 1.81% for R_2. Figure 1 shows intelligibility rates for words and pseudowords as a function of the reversion size.

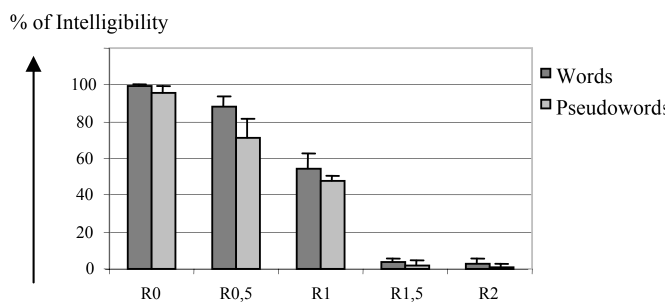

Figure 1: Rate of intelligibility for words and pseudowords plotted against the size of the reversion.

The subjects performed better overall with words than with pseudowords ($F(1,49)=158.5$; $p<.0001$). For both categories of stimuli the degradation of the first half syllable ($R_{0.5}$) gave high scores of restoration (average 79.65%). When a little part of the first syllable is degraded the cognitive system is able to reconstruct the signal. When only the first syllable is degraded scores turned around 50% as the second syllable was well identified. However, the degradation of one syllable and a half ($R_{1.5}$) gave disastrous reconstruction scores (below 3%). When the distortion is longer than the syllable the system seems to be unable to reconstruct neither the first syllable nor the second one which is only partly damaged. This tends to confirm the main role of the syllable as a unit in French comprehension processes.

Comparing words and pseudowords in condition R_1 (first syllable degraded) we observed that the first syllable is sometimes reconstructed only in words (so the whole word is found): 54.8% of words are reconstructed. In pseudowords the first syllable is almost never reconstructed (47.5% of reconstruction) moreover the degradation disturbs the well understanding of the second one (though it is intact).

In addition we observed that for pseudowords restitution participants tend to answer a real word phonological similar to the target instead of the right pseudoword. In average participants answer by a word for 3.65% (SD= 3.76) of the 120 pseudowords. For example the word "*parfum*" was frequently given as an answer of the target stimulus "*rafin*". This result shows the robustness of lexical effects in a non lexical task such as pseudowords restoration.

Furthermore we observed both a frequency effect ($F(1,49)=17.12$; $p=.0001$) and a neighbour effect ($F(1,49)=20.15$; $p<.0001$) on word reconstruction. The most frequent words were better reconstructed whatever the inversion degree was and words with fewer neighbours were also better reconstructed. The interaction between Frequency and Neighbour was significant only for condition R_1. This interaction indicates that when the first syllable is distorted the number of neighbours is the first criterion that could modify the reconstruction process. A high frequency could thus help the reconstruction but only for words with few phonological competitors.

The fact that pseudowords were more difficult to reconstruct than words seems coherent because pseudowords do not have any representation stored in the mental lexicon. Consequently, they do not benefit as much from lexical help. Overall performances for pseudowords were very homogenous over participants for most conditions (see Figure 2). However the condition $R_{0.5}$ showed a large interindividual variability. In this condition, some subjects were undisturbed by the inversion whereas others were deeply perturbed and failed the reconstruction task: performances ranged from 47.9% to 91.7% of correct reconstruction (mean=71.2%, SD=10.4).

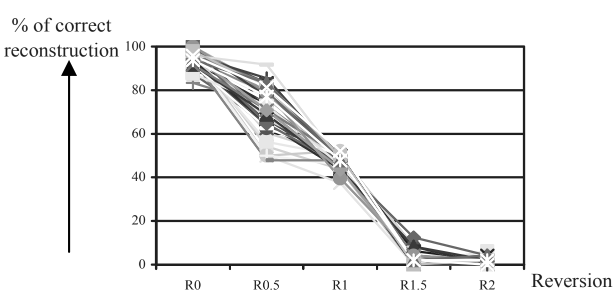

Figure 2: Reversed pseudowords reconstruction. Each curve represents the results of one subject.

Interestingly, this important variability was not observed for word reconstruction (% of reconstruction varied from 72.9% to 97.9%; mean= 88.2% SD=5.67). Moreover, speakers who had difficulties in reconstructing pseudowords in condition $R_{0.5}$ (63.2% of reconstruction for the 25 lowest and 78.5% for the 25 highest performing participants) had no trouble in reconstructing words in the same reversed condition (89.4% of words were reconstructed against 86.6% for higher score participants). The correlation between the performance for word and pseudoword reconstruction was not significant. This intriguing result suggests that lexical help can to some extent compensate poor performance on pseudoword reconstruction.

Pseudowords are considered as speech and thus general phonotactics apply (giving cues to the identity of the contiguous phonemes) but they do not have any representation stored in the mental lexicon. Consequently, reversed pseudoword reconstruction is primarily based on auditory information. So why did the subjects – all young and without any auditory problems – present such varied performances? Given that descending auditory pathways could interfere in speech perception and that their contribution is unequal among subjects, we can formulate the hypothesis that the MOCB functionality may be responsible for the behavioural results we observed. In order to answer this question we compared the results obtained for pseudoword reconstruction and auditory performance in each participant.

Experiment 2: Auditory measurements

Two groups of 10 persons each were then formed from the subjects in experiment 1 according to their performance for pseudowords reconstruction in condition $R_{0.5}$ (i.e., the condition showing the largest variability). The HP group (High Performance) was composed of the 10 persons who showed the best performances (m=83.3%). The LP group (Low Performance) was composed of the 10 subjects who showed the lowest performances (m=50%). We measured the functionality of the MOCB of these selected subjects (uncrossed pathway) in a soundproof room. OAEs were recorded according to the method of Bray and Kemp using the Otodynamics ILO88 measuring device. A miniaturized microphone placed in the external ear canal delivered acoustic stimulations (clicks) and recorded responses. For each participant we recorded OAEs for 20 ms after clicks delivery with and without a broadband noise (30dBSL) applied in the contralateral ear. We calculated the contralateral suppression of OAEs in each ear and the corresponding lateralization (for details see Veuillet, Collet & Bazin, 1999). The tests lasted one hour.

Participants The 20 participants selected from experiment 1 were all volunteers. They all had normal peripheral hearing (thresholds better than 20 dB HL between 250 Hz and 8000 Hz) and a normal tympanometry (stapedian reflex greater than 65 dB HL). The subjects had no history of otological or neurological disorders and all were right handed (more than 80% according to the Edinburgh test).

Results and Discussion

Results are clear cut: the HP group showed better contralateral suppressions in both ears than did the LP group. Table 2 shows the mean and the standard deviation of contralateral suppressions of OAEs in the right and left ears respectively, for each group of subjects. The last column indicates the lateralization (Contralateral suppression of OAEs on right ear minus left ear).

Table 2: Contralateral suppressions of OAEs.

	Right ear	Left ear	Lateralization
HP Group	- 4.2 (1.1)	-2.7 (1.8)	-1.5 (2)
LP Group	-1.4 (2)	-1.8 (1.3)	0.4 (1.6)

The ANOVA analysis ran on lateralisation showed a significant effect of the Group factor ($F(1,9)=7.64$; $p=.022$ see Figure 3): HP group was more lateralized on the right ear than LP group.

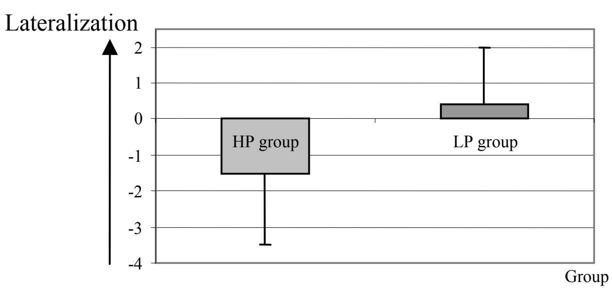

Figure 3: Lateralization for the two groups of subjects.

Indeed auditory areas are asymmetric and the peripheral auditory system reflects this asymmetry. An efficient MOCB is characterised by a large inhibitory power and by the lateralization (for right handed people, the more negative the lateralization the more efficient the MOCB).

Auditory measurements demonstrated clearly that the HP group had a better MOCB and was more right lateralized than the LP group. We found a correlation between behavioural performances and the lateralization of the subjects ($r=0.7$; $p<.001$). It suggests that the stronger the asymmetry of the auditory system the better the behavioural performances. This demonstrates the link between the MOCB and the cognitive processes of reversed speech restoration. The role of the MOCB could be to filter the damaged signal in order to highlight perception of those elements which are pertinent. The MOCB would be a sort of adapting mechanism of the ear to situations in which the signal is perceived.

Taken together, experiments 1 and 2 throw light on the participation of high and low-level mechanisms in reversed speech restoration.

Experiment 3: Electrophysiology

A third experiment using ERPs was run in order to describe the neuronal activity related to reversed speech comprehension. This experiment should allow us to reach complementary information about the temporal dynamics of high and low-level processes.

Materials and Methods

Stimuli 200 experimental disyllabic words selected from *Lexique* were included in 200 unpredictable context sentences (e.g., *Les parents choisissent des **prénoms** pour leurs enfants / Parents choose **first names** for their children*). We randomized the position of the target noun in the sentence (position 1, 2 or 3). Recordings and time inversions were identical to experiment 1. In each sentence only the target noun could be reversed. We presented target words in sentences to avoid the surprise effect provoked by the stimulus arrival that modify EEG recording.

Experimental procedure Electroencephalographic activity was continuously recorded using a geodesic cap (Geodesic Sensor Net™), fitted with 65 soft electrodes (Ag/AgCl) referenced to the vertex. Subjects wore headphones (SONY® MDR-Q22LP) binaurally delivering stimuli. Scalp voltages were amplified with a high input impedance amplifier (200 MΩ, Net Amps ™, Electrical Geodesics INC.); amplified analogue voltages (0.1-200 Hz bandpass) were sampled at 500 Hz. We tested five reversed conditions as in experiment 1.

Each participant was seated in front of a computer screen where general instructions were displayed. They heard the 200 sentences one by one and had to repeat each of them to the experimenter who recorded the answers. They did not type the answer as in Experiment 1 in order to move as little as possible to avoid motor artifacts on the EEG recording. The recording lasted 1 hour.

Participants 20 volunteer subjects participated in experiment 3.

Preprocessing of EEG recordings We analyzed the amplitude of the surface current (in µV) of ERP markers identified in temporal windows and the percentage of nouns correctly reconstructed. EEG recordings were segmented from 100 ms before to 900 ms after the onset of the target noun. A low-pass 30 Hz filter was applied, segments were re-referenced to an average-reference, and then a baseline correction was applied, based on the first 100 ms. Segments were averaged within each condition for each participant. Prior to averaging we rejected EEG portions contaminated by eye movements, eye-blinks, or transient amplifier saturation. The rate of rejection due to artifacts was about 10%. Further analyses are based on the data of 16 subjects.

Analyze of EEG recordings We selected seven scalp regions (Central, Central frontal, Right anterior, Left anterior, Central posterior, Right posterior, Left posterior) covering the whole scalp. After visual inspection of the Grand-Average waveforms, we identified two time-windows comprising the two main observed markers. The first time-window extends from 100 ms to 300 ms. The second one ranges from 400 ms to 750 ms. We performed repeated measures analysis of variance (ANOVA) with the factors: Time Window, Spatial region, Reversion and Syllable.

Results

We identified two waves characterized by two different peaks and latencies. In the first time-window we observed a negative fronto-central wave peaking around 180 ms. This wave can be categorized as the well-documented MMN (MisMatch Negativity) first described by Näätänen in 1978. According to the ANOVA including 7 spatial regions and 5 reversion conditions the wave was anterior ($F(6,90)=3.76$; $p<.005$) and appeared only for the reversed stimuli conditions and not for the control ($F(4,60)=3.5$; $p<.05$). This observation confirms former results from the literature showing that the MMN reflects the early detection of an auditory incongruity (Näätänen, 1990). Whenever a reversion was present in the target-word we observed a complete MMN independent of the reversion size.

In the second time-window we observed a globally-negative frontal wave, peaking around 600 ms. To our knowledge, this wave was not yet described in the literature so we will refer to it as the N600. The ANOVA showed an interaction between the spatial region and the reversion ($F(24,360)=1.95$; $p<.01$). To go further, we tested the syllable effect and found an interaction between the spatial region and the syllable ($F(1,15)=7.8$; $p<.05$) (Figure 4). It appears clear that the N600 is present only over frontal regions and only for reversions larger than one syllable.

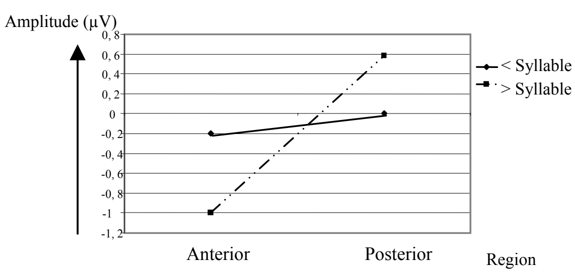

Figure 4: Interaction Spatial region X Syllable.

The N600 was modulated by the nature of the stimulus: When the reversion increases, the amplitude of the N600 increases too. The N600 seems to characterize high-level processes activated during speech reconstruction, whereas the MMN would reflect the detection of a transient degradation occurring in speech (Figure 5).

Lastly, the behavioural results from experiment 3 showed the same pattern as in experiment 1. The more the noun was distorted the more difficult it was to reconstruct it. However, we noticed better performances when words were presented in a sentential context than when they were isolated. For condition $R_{0.5}$ the reconstruction scores were 99.2% for words in sentences and 88.1% for isolated words and for condition R_1 the reconstruction scores were respectively 82.8% and 54.8%, whereas the sentence context did not allow guessing of the target noun (scores were inferior to 15% for conditions $R_{1.5}$ and R_2). The sentence context may activate lexical as well as context integration strategies that may help the reconstruction task.

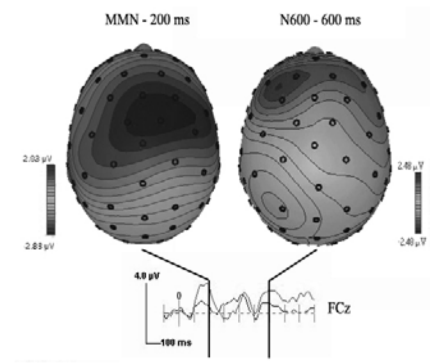

Figure 5: The MMN and N600 waves for word reconstruction in condition $R_{1.5}$. The electrophysiological line represents the condition R_0 (black) and the condition $R_{1.5}$ (grey).

General discussion

The aim of the study was to understand the respective influence of high and low-level mechanisms that underlie the cognitive reconstruction of degraded speech. Our results suggest that descending auditory pathways may intervene significantly during this process: more precisely, activity in MOCB may be one of the neurophysiological mechanisms participating in restoration process. In addition, high-level knowledge is activated to help the reconstruction. Speech comprehension is the result of an interaction between low-level mechanisms and elaborated knowledge stored in the mental lexicon. In experiment 1 we saw that the system was able to reconstruct speech signal to some extent. However reversed words and pseudowords are not reconstructed in the same way. For words both high and low-level mechanisms intervene, often resulting in successful comprehension. Both phonological neighbours and the frequency of noun effects suggest the implication of high-level mechanisms (lexical search) in word reconstruction. These mechanisms may either improve the signal reconstruction in a top-down scheme or more probably compensate for the lack of information if the low-level mechanisms fail to reconstruct the signal.

Pseudowords are not listed in the mental lexicon however; high-level mechanisms are still involved as demonstrated by the restitution of real words phonologically similar to pseudowords. In addition, our results showed a syllable effect. As long as the damaged information is shorter or equal to one syllable subjects still understand, even if the target item exhibits numerous phonological neighbours. When the distortion gets larger than one syllable, the reconstruction becomes more difficult. These results are consistent with the hypothesis that the syllable could be a perceptual unit in French.

Another interesting finding is the large variability observed between normal hearing persons for pseudoword reconstruction. For the reversion of the first half syllable some of the participants had no trouble in reconstructing pseudowords whereas others largely failed. Moreover, behavioural results and MOCB functionality of the subjects correlate significantly (experiment 2). This suggests implication of the efferent auditory pathways in reversed speech reconstruction. Reversed speech intelligibility seems to be linked with functioning MOCBs. The MOCB seems to modify the properties of auditory fibres in order to improve the ability of the auditory system to focus on pertinent information included in the percept. However, we did not find any correlation between auditory measurements and word reconstruction. The variability may fade during word reconstruction because of the intervention of lexical strategies which leads us to speculate on the importance of lexical strategies as a consequence of poor functionality of the MOCB. It would be interesting to test whether lexical strategies are more important to people with hearing impairments.

Experiment 3 showed an improvement in speech reconstruction in sentential context. Electrophysiological analyses showed both an MMN and an N600. The cortical generators of the MMN were located in the bilateral auditory cortices and associated to a frontal (right) generator that was linked to post-perceptual attentional controls driven by the MMN itself (Giard, Perrin, Pernier & Bouchet, 1990). During speech comprehension, the MMN could be considered as a fully automatic response to variation in the input that may allow attentional controls and on-line supervision that helps gating the information stream from perception to comprehension.

The N600 may characterize the implication of elaborated knowledge during speech restoration. Davis and Johnsrude (2003) showed that the frontal regions are recruited to help the restoration or in compensation process.

Conclusion & Perspectives

Speech reconstruction is the result of rapid, efficient activation of several complex mechanisms. Our experiments show that the respective involvements of the high and low-level mechanisms depend on the nature of the stimuli: pseudoword stimuli highlight the major role of the MOCB while word stimuli emphasize lexical strategies. At this point, we have shown that the amplitude of the N600 wave is modulated by the duration of the signal degradation. Further experiments will be necessary to precisely determine the role of each mechanism, and in the short term the extension of this experiment to hearing impaired patients is planned since it could lead to the development of new hearing aids.

Acknowledgments

This study was supported by an ACI (n° 67068) of the French *Ministère de l'Enseignement Supérieur et de la Recherche* attributed to Fanny Meunier. Authors would like to thank the "Institut des Sciences Cognitives" (Lyon – France) where EEG recordings took place.

References

Collet, L., Kemp, D. T., Veuillet, E., Duclaux, R., Moulin, A., & Morgnon, A. (1990). Effect of contralateral auditory stimuli on active cochlear micro-mechanical properties in human subjects. *Hearing Research*. *43***,** 251-262.

Content, A., Dumay, N., & Frauenfelder, U.H. (2000). The role of syllable structure in lexical segmentation in French. *In Proceedings of the Workshop on Spoken Word Access Processes, 29-31st May 2000*, Max-Planck Institute for Psycholinguistics, Nijmegen, The Netherlands.

Davis, M.H. & Johnsrude, I.S. (2003). Hierarchical processing of spoken language comprehension. *Journal of Neuroscience, 23*, 3423-3431.

Giard, M.-H., Perrin, F., Pernier, J. & Bouchet, P. (1990). Brain generators implicated in the processing of auditory stimulus deviance: A topographic event-related study. *Psychophysiology*, *27* (6), 627-640.

Giraud A.L., Garnier S, Micheyl C., Lina-Granade G, Chays A. & Chery-Croze S. (1997). Medial Olivocochlear Efferent Involved In Speech In Noise Intelligibility. *Neuroreport*, *8*, pp. 1779-1783.

Greenberg, S. & Arai, T. (2001). The relation between speech intelligibility and the complex modulation spectrum, *Proceedings of the 7th Eurospeech Conference on Speech Communication and Technology (Eurospeech-2001)*, pp. 473-476.

Khalfa, S. & Collet, L. (1996). Functional asymmetry of medial olivocochlear system in humans. Towards a peripheral auditory lateralization. *NeuroReport 7*, 993-996.

Kumar U. A. & Vanaja C. S. (2004). Functioning of olivocochlear bundle and speech perception in noise. *Ear and Hearing*. *25*(2):142-6.

McClelland, J.L. & Elman, J.L. (1986) The TRACE model of speech perception. *Cognitive Psychology 18*:1-86.

Meunier, F., Cenier, T., Barkat, M. & Magrin-Chagnolleau, I. (2002). Mesure d'intelligibilité de segments de parole à l'envers en français, *Actes des 24ème Journées d'étude sur la parole (JEP)*, p.117-120, Nancy, France.

Näätänen, R. (1990). The role of attention in auditory information processing as revealed by event-related potentials and other brain measures of cognitive function. *Behavioral and Brain Sciences*, *13*, 201-233.

New, B., Pallier, C., Ferrand, L., & Matos, R. (2001). Une base de données lexicales du français contemporain sur internet : LEXIQUE. *L'Année Psychologique*, *101*, 447-462.

Saberi, K. & Perrott, D. R. (1999). Cognitive restoration of reversed speech. *Nature*, 398, 760.

Veuillet E., Collet L. & Bazin F. (1999). Objective evidence of peripheral auditory disorders in learning-impaired children. *Journal of Audiological Medicine*, *8*(1): 18-29.