Journal of Speech,
Language, and
Hearing Research

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Journal:	*Journal of Speech, Language, and Hearing Research*
Manuscript ID:	JSLHR-L-06-0235.R3
Manuscript Type:	Research Article
Date Submitted by the Author:	n/a
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Speech Restoration: An Interactive Process

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Abstract:

Purpose: This study investigates our ability to understand degraded speech signals and explores to what extent this capacity is correlated with the functional characteristics of our peripheral auditory system.

Method: We evaluated the capability of 50 normal hearing native French-speakers to restore time-reversed speech. The task required them to transcribe two-syllable words and pseudowords containing temporal reversions of variable sizes, ranging from no reversion, to complete reversion, increasing by half-syllable steps. In parallel, the functionality of each participant's auditory efferent system was evaluated using contralateral suppression of click-evoked otoacoustic emissions.

Results: As expected, perceptual accuracy for time-reversed speech diminished when the size of the applied temporal distortion increased. A lexical benefit was evident, words being better reconstructed than pseudowords. An important interindividual variability in performance was observed specifically for pseudowords. Functional exploration of the auditory system revealed that speech restoration performances correlated with the suppression strength of the participant's auditory efferent system.

Conclusions: These results suggest a clear relation between the functional asymmetry of the auditory efferent pathway and the comprehension of acoustically distorted speech in normal hearing subjects. Further experiments are needed to better specify how the functionality of the MOCB can cause phonological activation to be more efficient.

Key Words

Degraded speech comprehension, Lateralization of audition, Medial Olivo Cochlear Bundle, Otoacoustic emissions

Manuscript

With the present study we explored the capacity of normal hearing people to understand distorted speech. Since this ability involves both auditory analysis of speech sound and linguistic processes, we studied their potential relationship through audiological and intelligibility performance measures. Most of the time, speech gets masked by environmental noise or concurrent speech; consequently, our cognitive system must be able to detect target signals from the masking and perform specific processes on the sparse and distorted speech signal it receives in order to maintain perception and intelligibility. The auditory and cognitive processes engaged are able, to some extent, to correct errors due to distortion of the signal.

Several studies have experimentally shown that speech remains understandable in spite of acoustic degradations. It was for example demonstrated that speech could remain intelligible even when reduced to only four spectral channels (Remez, Rubin, Pisoni, & Carrell, 1981; Shannon, Zeng, Kamath, Wygonski, & Ekelid, 1995), when its spectral extent was drastically restricted (Warren, Riener, Bashford, & Brubaker, 1995; Lippman, 1996) or when its spectro-temporal coherence was significantly altered (Arai & Greenberg, 1998). In a neuroimaging experiment investigating the cortical regions implicated in the reconstruction of distorted speech, Davis and Johnsrude (2003) manipulated the surface properties of speech in three different ways: a) interrupted speech was generated by interleaving noise bursts of increasing length (500, 200 or 100 ms) with 200 ms long original speech segments, b) noise vocoded speech was obtained by restricting the spectrotemporal content of speech to 4, 7 or 15 spectral channels of amplitude-modulated noise and c) speech in noise was created by adding speech-spectrum noise over an original speech signal at signal-to-noise ratios of -1, -4 or -6 dB. Intelligibility of all different signals was assessed and a correlation analysis used in order to identify brain activity associated with the compensation of acoustic distortions in speech.

Regions implicated in the general process of reconstructing degraded speech, independently of the nature of the distortion, were then identified. They included in particular the left inferior frontal gyrus, suggesting the activation of generic reconstruction processes (see also Warren, Bashford, Healy, & Brubaker, 1994). Even if the existence of compensatory mechanisms allowing the intelligibility of degraded speech has been established, the cognitive processes involved, as well as their physiological correlates, are far from being clearly identified and understood. The purposes of the present study were firstly to examine the ability of normal-hearing listeners to restore distorted speech and secondly to investigate the relationship between auditory processing and the cognitive restoration of degraded speech in order to understand the complex interactive procedures involved during the comprehension of natural speech.

Speech comprehension relies on the tight interplay between high-level mechanisms, i.e. linguistic-specific information processes and more general low-level mechanisms, i.e. auditory perception. Interactions of this nature have often been observed for language processing. For example, it has been established that linguistic rules acquired for the processing of one’s native language during the first few months of life shape the perception of speech sounds for the rest of one’s life (e.g. Mehler & Dupoux, 2006, among others). This modulation of sound perception by specific linguistic knowledge acquired during early exposure is observed at various linguistic levels. For instance, knowledge about the phonetic constraints of a language modifies the perception of speech sounds, even if they are meaningless. Dupoux, Kakehi, Hirose, Pallier, and Mehler (1999) presented Japanese participants with French pseudowords containing consonantal clusters inexistent in Japanese (like plosive-fricative clusters). Participants perceived an “illusory” epenthetic vowel [ʊ] inside consonant clusters in VCCV stimuli and were unable to discriminate between VCCV and VC[ʊ]CV sequences, showing that the participant’s knowledge of Japanese modified their space of possible phonological perceptions, excluding typical French clusters absent from their language. In addition, knowledge about lexical phonotactic constraints in a specific language can be used during the word segmentation process of continuous speech (Norris, McQueen, Cutler, & Butterfield, 1997). At another level, semantic and lexical expectancies about words presented in context can create illusory perceptions in physically distorted words (Warren, 1970; Samuel, 1996). For instance, in the context of phonemic restoration, a word in which a portion has been replaced by a broadband noise is perceived as the intact word and listeners cannot identify the locus of the replacement. However, when the missing part of the word is replaced by silence, listeners correctly localize the gap, and the absence of speech sound is detected, demonstrating that phonemic restoration depends on the type of distortion applied (Warren, 1970). At a higher level, it was shown that the recognition of real words slows down as the number of phonological neighbors in the language (words sharing phonological properties with each other such as *green*, *Greek, freak* etc.) increases, while for pseudowords, that do not have a stored representation in the mental lexicon, the reversed effect was observed: their recognition speeds up as phonotactic probability gets higher (Vitevitch & Luce, 1999). These results reflect the fact that stored representations of words in our mental lexicon modify the way we process incoming lexical items and ultimately understand them. All the above mentioned effects reflect the way the system uses specific representations and optimizes speech sound processing in order to facilitate real-time word recognition. In order to look at lexical influences on speech restoration processes, an initial experiment was designed to contrast the restoration of words and pseudowords. This comparison allowed us to evaluate the involvement of lexical help during distorted speech comprehension. Subsequently, in order to understand the influence of the auditory system in speech restoration processes we evaluated the efficiency of the auditory system of our normal-hearing participants. To this end, we made several auditory measurements evaluating different functional aspects of the peripheral auditory system, including pure-tone thresholds (evaluating perceptual sensitivity to pure-tones), stapedial reflexes (evaluating the integrity of the middle ear transfer function), and tympanometry (verifying the integrity of the tympanic membrane). Furthermore, a protocol of contralateral suppression of otoacoustic emissions was conducted in order to evaluate the functionality of the medial olivocochlear bundle (MOCB), a major peripheral auditory efferent pathway modulating cochlear amplification (Cooper & Guinan, 2006). Since only MOCB function showed significant links with our behavioral results, we will focus primarily on this specific pathway in the following part of the introduction.

Speech is first encoded within the peripheral sensory system and then at the central nervous level. Speech signals are primarily transmitted along ascending auditory pathways that carry acoustical information to the primary auditory cortices via a number of sub-cortical relays. In parallel with these ascending pathways, several efferent pathways propagating information back to the cochlea have also been described (Rasmussen, 1946; Warr & Guinan, 1979; Huffman & Henson, 1990). Amongst them, the MOCB, which originates in the superior olivary complex and synapses both ipsilaterally and contralaterally with the outer hair cells of the cochlea, has been the object of particular attention (Warr, Guinan, & White, 1986). Indeed, in humans there are several lines of functional evidence that cortical influence on the cochlear micromechanical properties could be exerted via the MOCB, as suggested by studies of cortically resected patients (Khalfa et al., 2001) or electrical cortical stimulation in epileptic patients (Perrot et al., 2006). About 75% of MOCB fibers connect with outer hair cells on the contralateral cochlea, while the remaining 25% terminate on outer hair cells of the ipsilateral cochlea. It is possible to evaluate the extent to which suppression mediated by the uncrossed MOCB occurs by measuring the contralateral suppression of otoacoustic emissions (OAEs) (Collet, Kemp, Veuillet, Duclaux, Moulin, & Morgon, 1990; Veuillet, Collet, & Duclaux, 1991; Kujawa, Glattke, Fallon, & Bobbin, 1993). During this procedure, the MOCB is activated with contralateral noise and the effects of this activation correspond to the reduction in amplitude of the evoked-OAEs (EOAEs) measured in the ipsilateral ear. The contralateral stimulus is propagated by afferent pathways that are, in their majority, crossed. These fibers thus stimulate the ipsilateral superior olivary complex. In the ipsilateral ear it is then possible to record OAEs reduced by the uncrossed pathway of the ipsilateral fibers of the MOCB. Therefore contralateral suppression of EOAEs is a reflection of MOCB activity and this measure is stable over time (Morand, Collet, & Veuillet, 2000), although, wide inter-individual variations in MOCB activity have been observed in normal-hearing people (Collet, Veuillet, Bene, & Morgon, 1992). Interestingly, MOCB functionality is usually asymmetrical and presents ear advantages. While uncrossed MOCB fibers show a statistically significant functional asymmetry (the right-side activity is greater than the left-side activity in right-handed subjects, Khalfa & Collet, 1996), the crossed pathway shows a reverse asymmetry (*i.e.* a left-ear advantage, Philibert, Veuillet, & Collet, 1998).

Although its precise and entire role is still unclear, the MOCB is more and more often associated with speech perception. MOCB efficiency was initially related to selective frequency encoding, improvement of signal-to-noise ratio, detection of pure, complex tones in the presence of binaural noise, spectral analysis, temporal analysis, and intensity discrimination of pure tones in noise (Micheyl & Collet, 1996; Micheyl, Morlet, Giraud, Collet, & Morgon, 1995; Micheyl, Perrot, & Collet, 1997). Recent studies have proposed that sub-cortical neural systems including the MOCB are recruited in the comprehension of speech presented in unfavorable acoustic conditions (Kumar & Vanaja, 2004; May, Budelis, & Niparko, 2004; Tomchik & Lu, 2006). In particular, one study suggested that the MOCB could play a role in the comprehension of distorted speech such as speech in noise (Giraud, Garnier, Micheyl, Lina-Granade, Chays, & Chery-Croze, 1997). In this study the authors compared measures of speech in noise intelligibility in vestibular neurotomized patients (efferent fibers cut) and in normal-hearing participants. Their experiments used vocal audiometry in monaural and binaural noise. Results showed that contralateral noise improves speech intelligibility for normal participants in correlation with the degree of suppression by their MOCB: the more suppression from their MOCB, the more benefit from the contralateral noise. Conversely, no improvement was observed with neurotomized patients. This suggests a peripheral role of the MOCB, such as an antimasking function in the perception of speech in noisy environments and more generally that the MOCB could have an important role during speech perception. These results led us to investigate the functionality of the MOCB of our participants to see if there is a link between these fibers' functionality and distorted speech comprehension. Our study investigates the capacity to understand degraded speech signals and explore to what extent it is correlated with the functionality of the peripheral auditory system. The purpose of this interdisciplinary study was to point out that not only high level processes intervene in degraded speech but also processes from lower levels such as the olivocochlear loop.

In the first part of our study, we investigated lexical influence on the ability to restore distorted speech. We asked participants to report words and pseudowords that contained increasing portions of distorted signal. The distortion applied consisted in a partial reversal of the original speech signal along its temporal dimension. Time reversal of local segments of a spoken sentence was described as "the most drastic form of time scale distortion" by Licklider and Miller (1960). Although the amplitude of speech is not modified by time reversal, the temporal envelope and the fine structure of the running spectrum are affected in time-reversed sounds, depending on the duration of the reversal window (Saberi & Perrott, 1999). As time-reversed speech has many characteristics in common with natural speech, it has often been used as a control condition for speech in experiments on the human ability to process language (see for instance Mehler, Jusczyk, Lambertz, Halsted, Bertoncini, & Amiel-Tison, 1988). However, some experiments have shown that the human perceptual system is to some extent able to handle speech inversion. For example, Saberi and Perrott (1999) found that speech intelligibility is resistant to the effects of time reversal of local segments of a spoken English sentence. They used sentences that were segmented as sequences of constant duration frames. Each frame was time-reversed, resulting in stimuli that preserved the long term structure of speech (frame positions were not permuted along the sentences) but exhibited local time-reversal. They tested several time window inversions (from 50 to 200 ms) and showed that intelligibility was intact for 50 ms segment durations while a 50% intelligibility occurred for about 130 ms of inversion (see also Greenberg & Arai, 2001; and Meunier, Cenier, Barkat, & Magrin-Chagnolleau, 2002 for experiments respectively in English and in French).

In our experiment and in order to look at lexical influences, we compared intelligibility performances for disyllabic words and pseudowords that had both been distorted. Contrarily to what was done in previous experiments (Saberi & Perrott, 1999; Greenberg & Arai, 2001; Meunier, Cenier, Barkat, & Magrin-Chagnolleau, 2002), we used a linguistic unit, the syllable as the unit of degradation instead of a raw uniform temporal segmentation. For each item, we distorted either half a syllable, the first syllable, the first syllable plus half of the second or the whole item. We expected to assess the importance of the syllable as a unit in French comprehension and differences in performance between word and pseudoword restoration to better understand the mechanisms involved in lexical access. In light of the interindividual variations observed in behavioral performances, we next explored the auditory system of two groups of selected participants and evaluated the functionality of their MOCB. We further examined fine differences in the degree of MOCB suppression in both ears to assess the lateralization of their auditory areas.

Speech Restoration Measures

Method

Participants. 50 students (22 females and 28 males) aged between 18 and 25 participated in this study. None had any known auditory or language problems. They were all volunteers and native French speakers.

Stimuli. Word stimuli consisted of 120 disyllabic French common nouns. They were all part of the most common vocabulary words in the language, with lexical frequency ranging from 0.29 to 387.03 occurrence per million words (using the *Lexique* database, New, Pallier, Ferrand, & Matos, 2001). We also constructed 120 experimental disyllabic pseudowords using the same syllables contained in the 120 experimental words. These pseudowords resulted from syllable switching and satisfied the phonotactic constraints for French. All 240 items were recorded in a soundproof room by a native French female speaker and stored as Windows PCM files (22 KHz, mono, 16 bits).

For each disyllabic item, the beginning of the first and second syllable, as well as the end of the item were manually tagged by a French native speaker. The temporal midpoint of each syllable was thus automatically marked and used to define the half syllable. An acoustic time-reversal procedure was then applied to each of the 240 disyllabic items to give five experimental conditions: no reversal applied (condition R_0); first half syllable time-reversed (condition $R_{0.5}$), first syllable time-reversed (condition R_1), first syllable and a half time-reversed (condition $R_{1.5}$), entire item time-reversed (condition R_2). Time reversion consists of reversing the temporal order of the waveform samples within the frame of interest, the frame extending from null to two syllables by steps of one-half syllable depending on the condition. This procedure does not result in a simple temporal reorganization across phonemes but in a deeper modification since the internal dynamics of the phonemes are reversed. An orthographic analogy of a time-reversal of the first syllable in the word “caddie” would be the stimulus “ʂɔddie” (with “ca” mirrored into “ʂɔ”) rather than “acddie”.

Procedure. The experiment took place in a quiet room and lasted for about 50 minutes. Participants faced a computer monitor (PC type) and the stimuli were delivered binaurally via headphones (Beyerdynamic DT 48, 200 Ω) at a comfortable level of hearing (80 dB). The presentation order within the 120 word stimuli block was randomized across participants and randomization was also applied to the 120 pseudoword stimuli block. Half the participants started with words and half started with pseudowords. They were told whether they would be hearing words or pseudowords and were asked to transcribe what they had understood on a computer keyboard.

Results

All participants and items were included in the analyses. We defined the percentage of restoration as the number of syllables correctly transcribed from the stimuli brought to a 100 baseline. Thus 50 % restoration corresponds to an average of one accurately transcribed syllable from the two syllables originally constituting the stimuli. We compared the average percentages of restoration for words and pseudowords across all conditions. Statistical significance was measured via repeated measures analysis of variance (ANOVA) performed with the individual percentage of restoration as a dependent variable, reversion size and lexicality (words vs. pseudowords) as within-subject factors, the measures being repeated over subjects.

High-level lexical compensation mechanisms in distorted speech comprehension. The average restoration score was 97.3% for condition R_0; 79.7% for $R_{0.5}$; 51.2% for R_1; 2.9% for $R_{1.5}$ and 1.8% for R_2. Taken as a whole, the percentage of intelligibility decreased as the amount of distortion increased (see Figure 1) ($F(4, 196) = 7919$, $p < .0001$, $\eta^2 = .99$). Participants performed better overall with words than with pseudowords (49.5% vs. 43.4%; $F(1, 49) = 154$, $p < .0001$, $\eta^2 = .76$), suggesting a lexical effect in reconstructing distorted speech items (see Figure 2). This effect was present for each of our reversal conditions: $F(1, 49) = 44.9$, $p < .0001$, $\eta^2 = .48$. for R_0 ; $F(1, 49) = 87.94$, $p < .0001$, $\eta^2 = .64$ for $R_{0.5}$; $F(1, 49) = 42.16$, $p < .0001$, $\eta^2 = .46$ for R_1 ; $F(1, 49) = 7.23$, $p < .01$, $\eta^2 = .13$ for $R_{1.5}$ and $F(1, 49) = 14.53$, $p < .001$, $\eta^2 = .23$ for R_2. The second level interaction between Type of items and Reversal was significant ($F(4, 196) = 42.87$, $p < .0001$, $\eta^2 = .47$) and easily explained by the quantitative modulation of the lexical effect, the latter being maximal in condition $R_{0.5}$ and minimal but still significant in condition R_2.

For both the word and pseudoword categories, degradation of the first half syllable ($R_{0.5}$) gave high restoration scores (average 79.7%). When half the first syllable was distorted the cognitive system was generally able to reconstruct the signal. When the whole of the first syllable was distorted, scores were around 50% as the second syllable was still well identified. However, the degradation of one and a half syllables ($R_{1.5}$) gave very poor restoration scores (below 3%). When the distortion was longer than one syllable the participants seemed unable to reconstruct either the first or the second syllable, even though the latter was only partly distorted. With condition R_1, the first syllable was sometimes reconstructed in the word condition (54.8% restoration) while in the pseudoword condition this was not the case, the degradation even disturbing perception of the second syllable even though it was intact (47.5% restoration).

Interindividual variability in the absence of any lexical compensation effect. In general, performances for words and pseudowords were quite homogeneous across participants (*SD*s = 4.1 for words and 4.39 for pseudowords) except the $R_{0.5}$ pseudoword condition which showed wide variations across participants (*SD* = 10.4 while in other conditions interindividual variability was restrained between 1.64 and 3.65). In the $R_{0.5}$ pseudoword condition, some participants were undisturbed by the first half-syllable reversion, while others were deeply perturbed and failed the restoration task: individual performances for correct restoration ranged from 47.9% to 91.7% (*M* = 71.2%, see Figure 3). This means that some participants were mostly unaffected by the time reversal and able to report the stimulus as if it were intact while others were so disturbed that they were unable even to properly understand the unreversed second syllable.

Discussion

This experiment showed two main effects: an effect of the syllable unit and a lexical effect. Using the syllable as the distortion unit showed that when the distortion is shorter than a syllable, items remain mostly intelligible while when the distortion is longer than the syllable, the cognitive system is unable to reconstruct either the first syllable or the second one even though the latter is only partly distorted. This tends to confirm the critical perceptual role of the syllable in French language comprehension processes. We will discuss this point further in the general discussion.

A lexical effect appears clearly: pseudowords were more difficult to reconstruct than words; the current findings are consistent with studies that reveal the specific linguistic knowledge effect which affects speech perception. For example, Frauenfelder, Segui and Dijkstra (1990), defining the word superiority effect, showed that speech sounds are better perceived when they are part of real words than when they are embedded in a pseudoword. Moreover, a closer look at the type of errors made by our participants showed that the answers were biased toward existing words phonologically close to the target pseudoword, strengthening the idea of a word superiority effect for the perceived items. On average participants answered with a word for 3.7% (*SD* = 3.76) of the 120 pseudowords. This percentage is quite high if we consider that the participants had no time-limit for the task and thus had time to remember the instructions specifying that the correct answers were not existing words. For example the word *parfum* "perfume" was frequently given as an answer for the pseudoword-target *rafin*. This result shows the robustness of the word superiority effect in a nonlexical task such as pseudoword restoration.

Last but not least, it is noticeable that performances for words were more homogeneous among participants than the pattern observed for pseudowords. Pseudowords are made of natural speech and thus follow general phonotactic constraints; contiguous phonemes give cues about the identity of their neighboring phonemes. However, even if pseudowords benefit from phonotactic knowledge of the language they never have been heard before and do not have any stored lexical representation. Consequently, time-reversed pseudoword restoration is primarily based on auditory information processing. Pseudoword comprehension scores may therefore be correlated with characteristics of the auditory system, and particularly with characteristics that vary a lot for normal hearing individuals, such as the functionality of auditory efferents (see Collet, Veuillet, Bene, & Morgon, 1992). To test if the auditory capacity could shed light on the interindividual variability we observed for pseudoword restoration we made a battery of auditory measurements, and in particular the functionality of auditory efferents, for two contrasted groups of participants: A High Performance group (HP group) and a Low Performance group (LP group).

Auditory Measurements

Method

Participants. Two groups of 10 participants were selected from behavioral data obtained in Experiment 1 based on their performances for pseudoword restoration in condition $R_{0.5}$ (i.e., the condition showing the largest variability). The HP group (High Performance) was composed of the 10 persons (5 males, 5 females) with the best performances (*M* = 83.3%). The LP group (Low Performance) was composed of the 10 participants (5 males, 5 females) with the lowest performances (M = 50%). No participant had any history of otological or neurological disorders and all were right-handed (score of more than 80% according to the Edinburgh Hand Preference Inventory, Oldfield, 1971).

Procedure and apparatus. Firstly, we investigated the hearing sensitivity (threshold levels) of the participants. Thresholds were measured with a two-channel Clinical Audiometer AC40 Interacoustics and a Telephonics TDH 39P headphone. Secondly, we tested their stapedial reflexes using a Grason Stadler GSI33 Middle Ear Analyzer.

The degree of suppression of MOCB activity (uncrossed pathway) in the selected participants was also measured. The MOCB has been non-invasively investigated by recording EOAEs, sounds produced by the outer hair cells of the cochlea, in the external ear canal (Kemp, 1978). Click-EOAEs (CEOAEs) are recorded with and without a contralateral acoustic stimulation applied at 30 dB SL. The contralateral acoustic stimulation activates the medial olivocochlear efferent fibers and when these pathways are functional a decrease in CEOAE amplitude is observed (Collet, Kemp, Veuillet, Duclaux, Moulin, & Morgon, 1990; Veuillet, Collet, & Duclaux, 1991). CEOAEs were recorded according to the method of Bray and Kemp (1987) using the Otodynamics Analyser ILO88 (V3.92 system) measuring device. A miniaturized probe placed in the external ear canal delivered the acoustic stimulation (clicks, 80 µs rectangular electric pulses at 50 Hz) and recorded responses which were windowed from 3.2 to 20 ms after click delivery. Firstly, CEOAEs evoked by a non-filtered click at 80 +/-3 dB were measured in order to evaluate the amplitude and spectral quality of the response of both ears. To avoid artefacts due to greater stimulus intensity, this first recording used the non-linear differential mode in which three clicks were of the same polarity and equal amplitude but the fourth was of opposite polarity and three times the previous amplitude. It allowed recording of the nonlinear residual response emanating only from the cochlea and not from the middle ear (Veuillet et al., 1999). Secondly, the MOC system was explored using low stimulus levels (five intensities between 54 and 72 dB in 3 dB steps) which allow the use of the linear acquisition mode (i.e. four clicks of the same polarity and amplitude). Presentation of the selected stimuli was random for each ear. The contralateral ear was stimulated with a broadband noise delivered by an audiometer (called “speech noise”) presented at 30 dB SL above the auditory threshold of the subject (above the detection thresholds of the speech noise). The intrameatal intensities were chosen to be above the EOAE threshold and under the EOAE amplitude saturation (Veuillet, Collet, & Bazin, 1999). Responses were band-pass filtered between 500 Hz and 6000 Hz. We calculated the contralateral suppression of CEOAEs for each ear, the equivalent attenuation (EA) and the asymmetry index (AI) which corresponds to the difference in EA between right and left ears (for details see Veuillet et al., 1999). EA (expressed in dB) corresponds to the reduction in ipsilateral stimulus causing the same CEOAE reduction as a 30 dB SL contralateral acoustic stimulation (see Veuillet et al., 1999 for details concerning the calculation). The lower the EA value (which is negative when the efferent fibers inhibit the contraction of the outer hair cell), the greater the effectiveness of the MOCB. AI corresponds to EA obtained in the right ear minus EA obtained in the left ear. A negative value indicates a right ear advantage (right MOCB more suppressive than the left one) and a positive value a left ear advantage. This auditory testing program lasted 45 minutes.

Results

All participants had normal-hearing sensitivity i.e. hearing threshold levels below 20 dB HL between 250 Hz and 8000 Hz at octave frequencies. They all also had normal tympanometric recordings: stapedial reflexes were present with thresholds > 70 dB SPL.

Medial olivocochlear efferent system efficiency.

Table 1 compares the functioning of the MOCB between the two groups. The results are clear cut. The HP group showed better contralateral suppression in both ears than did the LP group: -4.2 dB and -2.71 dB respectively in right and left ears for the HP Group, and -1.38 dB and -

1.79 dB for the LP Group. Analyses of variance (one-way ANOVAs) on contralateral suppression of OAEs and on lateralization of the participants for each group were performed. The HP Group showed better suppressions in the right ear ($F(1, 18) = 15.32$, $p = .001$, $\eta^2 = .46$) and better lateralization scores ($F(1, 18) = 5.37$, $p < .05$, $\eta^2 = .23$). Contralateral suppressions in left ears were not significantly different between the HP and LP groups ($F(1, 18) = 1.73$, $p = .21$). According to these results, participants in the HP group were more lateralized on the right ear than participants in the LP group (Figure 4).

Medial olivocochlear efferent system efficiency and the comprehension of distorted speech. In addition we tested linear coefficient correlations (Pearson's r) between means of percentage of pseudoword restoration from behavioral performances and suppression of OAEs in both of the participants' ears and between means of percentage of restoration from behavioral performances and lateralization of the participants. We found a strong negative correlation between pseudoword restoration performances (mean of results obtained for all conditions) and suppression of OAEs in participants' right ears ($r = -0.7$, $p < .001$). We observed a non significant negative correlation between pseudoword restoration performances and suppression of OAEs in left ears ($r = -0.28$, $p = .23$) and a significant negative correlation between pseudoword restoration performances and lateralization of the participants ($r = -0.51$, $p < .05$).

Discussion

Auditory tests showed that the HP Group had better contralateral suppressions of OAEs in both ears than the LP Group. Asymmetry indexes showed that participants in the HP Group were more lateralized on the right ear than participants in the LP Group even though all participants were right-handed; this suggested that the HP Group had a right-side dominance of the MOCB. Indeed, auditory cortical areas are asymmetric and the peripheral auditory system reflects this asymmetry. The olivocochlear system is involved in language processing and shows an asymmetrical pattern of functioning influenced by handedness in the same way as hemispheric language representation (Khalfa, Veuillet, & Collet, 1998). When the MOCB functions normally, it is characterized by a large inhibitory power (suppression strength) and by lateralization. For right-handed persons, the more negative the lateralization the more suppressive the right-side MOCB is. Our results clearly demonstrated that the HP group had a more suppressive MOCB and was more right-lateralized than the LP group.

The correlation between behavioral performance and lateralization of the participants' auditory system suggests that the stronger the asymmetry of the auditory system the higher the behavioral performances. These results suggest the existence of a link between peripheral asymmetry and the cognitive capacities to restore time-reversed speech. However, as we will see in the general discussion, it is still unclear how direct this link is and further experiments are needed to elucidate this point.

General Discussion

In the present experiment we studied how normal-hearing participants were able to process auditory words and pseudowords containing temporal acoustic perturbations. Participants were asked to listen to and transcribe disyllabic sequences, which could be words or pseudowords. These items were distorted by time-reversals of the first half syllable (condition $R_{0.5}$), the first syllable (R_1), the first syllable and a half ($R_{1.5}$) or the entire item (R_2). For words, we observed that acoustical perturbations spanning less than one syllable could easily be overcome and that participants were mostly able to reconstruct parts of the missing signal. This was not the case for pseudowords. The $R_{0.5}$ condition for pseudowords gave rise to highly variable performances across participants. From their performance in the $R_{0.5}$ condition with pseudowords, we selected two groups of low and high performing individuals and measured their auditory capacities. There was only one but important functional auditory distinction between the two groups: the suppression capacity and lateralization index of their MOCB. Poor performers with time-reversed speech showed reduced MOCB asymmetry and suppression capacity compared to high performing individuals.

First of all, our behavioral results indicate a loss of intelligibility with an increase in the length of the inverted segments. Previous experiments have already given similar results, using altered sentences in English and French (Greenberg & Arai, 2001; Meunier et al., 2002). Our experiment confirms this ability of the human cognitive system to restore, to some degree, speech segments which have been inverted. However since the time-reversals were done on sentences and not on specific words in the previous experiments, the results are not directly comparable. Furthermore, while previous studies using time reversal referred to acoustic spans (duration in ms), our study is the first to use an explicit linguistic unit: the syllable. Results confirm the relevance of the syllable span for comprehension of French. Indeed, taking together word and pseudoword performances, while in the half syllable condition participants reached 79.7% identification, correct identification fell to 51.2% when the whole first syllable was distorted. This can be taken as evidence of the role of the syllable in perception. In French, the syllable has been proposed as a perceptual unit. For example, Mehler, Dommergues, Frauenfelder, and Segui (1981) demonstrated that in French a sequence is detected faster when it corresponds to a syllable than when it does not. For example, the sound sequence /ba/ is faster detected in [ba.lãs][1] 'balance' than in [bal. kõ] 'balcony'. These results were interpreted as reflecting the importance of syllables as perceptual units during recognition of French. This syllabic effect is not observed, for instance, in English (Cutler, Mehler, Norris, & Segui, 1986). Authors found that English participants were not influenced by the syllabic structure of the stimuli. Participants detected /ba/ and /bal/ as fast in [ba.lãs] as in [bal.kõ] regardless of syllabic structure. Moreover,

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[1] The word falls in two syllables according to the dot.

authors observed that French listeners use a syllable segmentation strategy when processing English words. Cutler et al. (1986) proposed that the segmentation strategy depends on the mother tongue of the listeners.

Our behavioral data also showed that words are better recognized than matched pseudowords; this is a well known effect in speech perception, called the word superiority effect (Frauenfelder et al., 1990). Henderson (1985) showed for example that interconnections between words facilitate word activation in the mental lexicon and preclude pseudoword processing. Since existing words correspond to stored representations in our mental lexicon, the analysis of speech signals corresponding to words is facilitated. Furthermore, the analysis of speech signals corresponding to auditorily close pseudowords can be biased in favor of word interpretation. This word superiority effect corresponds to top-down influences of lexical representations onto speech sound perception. Individual results observed for distorted word comprehension showed that this lexical compensation was almost always present (of the 50 participants only one participant showed better results for pseudowords and two gave similar performances with the two types of items).

In one particular condition, consisting in a time-reversal of the first half syllable ($R_{0.5}$) of pseudowords, participants exhibited very large variations in their capacity to report speech sounds (from 48% to 92% restoration). To understand these variations and look at low level processing involved in speech restoration we then tested the MOCB efficiency of our participants. The difference observed between our two groups of selected participants concerning their MOCB efficiency does not mean that other abilities are not involved in speech restoration, but that among our normal-hearing participants, it seems that performance was linked to the functioning of the MOCB. Participants with poor restoration of time-reversed speech showed reduced MOCB asymmetry and functionality compared to highly performing individuals. This result could suggest that the MOCB efferent system is involved in speech perception although its exact role in our behavioral experiment is unclear. Previous human studies, mostly done presenting acoustic signals in noise, give some leads. For example, Micheyl and Collet (1996) investigated the involvement of auditory efferents in hearing-in-noise situations, by comparing olivocochlear bundle (OCB) activity and detection-in-noise abilities in humans. Using OAE contralateral attenuation to test OCB involvement in the detection of signals in noise, they observed correlations between the contralateral attenuation of OAEs and tone-in-noise thresholds (detection thresholds for mid-frequency tones embedded in a 50 dB SPL binaural broadband noise and detection threshold shift induced by contralateral noise respectively) measured in the same participants. In the cochlea, efferent fibers inhibit OAEs by modifying contraction of the hair cells. This can lead to an increase in the signal-to-noise ratio for certain frequency bands in the signal (Cooper & Guinan, 2006). Therefore, the MOCB could act as a filter for the distorted signal in order to highlight perception of those elements which are pertinent. This functional capacity may of course be very important in natural speech comprehension where speech occurs in the presence of concurrent noises that may distort the speech signals reaching the ears. In these cases, the MOCB could facilitate the extraction of relevant sound information from concurrent background noise making it easier to extract good or distorted portions of speech sounds. The MOCB is certainly involved in suppression effects and consequently in sounds in noise processing. However involvement of the MOCB in time-reversed speech processing, where no noise is added, has so far not been directly established. In our study, the MOCB might have been excited during speech restoration due to the binaural presentation of the speech sounds. To verify this hypothesis it could be interesting, for instance, to evaluate the participant’s capacities to restore reversed speech while explicitly activating these auditory pathways with a broadband noise (this technique was used by Giraud et al., 1997). Further research is needed to understand more precisely how the physiological processes occur at peripheral levels in normal-hearing systems.

Another point that leads to an alternative interpretation of our correlation effect needs to be discussed: the MOCB lateralization and particularly the right-side dominance in right-handed persons. As the auditory pathways are crossed, acoustic signals perceived in the right ear are processed in the left auditory cortex, suggesting that MOCB lateralization may be linked to the lateralization of language functions. According to Pujol, Deus, Losilla, and Capdevilla (1999), 96% of right-handed participants are left hemisphere dominant for language functions. Recently, Powell and collaborators (Powell, Parker, Alexander, Symms, Boulby, Wheeler-Kingshott, et al., 2006) while testing connectivity between functionally defined language areas in frontal and temporal lobes, observed stronger connections between language areas in the dominant left hemisphere than in the corresponding areas in the right hemisphere. A recent study by Parker, Luzzi, Alexander, Wheeler-Kingshott, Ciccarelli, and Lambon Ralph (2005) using MRI tractography to investigate auditory-language pathways in the brain, showed stronger connections in the dominant hemisphere (see also Scott, Blank, Rosen & Wise, 2000). This clear structural asymmetry is interpreted as reflecting the left-sided lateralization of the language function in the human brain. It is further possible that language lateralization correlates with MOCB lateralization. This assumption is in line with recent results. For example, considering schizophrenic patients for whom there is no MOCB lateralization (Veuillet, Georgieff, Philibert, Dalery, Marie-Cardine, & Collet, 2001), a functional imaging study showed that they had less language lateralization than their healthy counterparts (Sommer, Ramsey, Mandl, & Kahn, 2003). In a recent paper, Veuillet and colleagues (Veuillet, Magnan, Ecalle, Thai-Van, & Collet, 2007) reported a study in which they showed that children with an auditory processing disorder (APD) associated with a dyslexic syndrome showed less lateralization of MOCB functionality than a group of matched normal reading children without APD, suggesting a link between the functional asymmetry of the MOCB and efficient phonological processing or phonological-to-visual word-form mapping. Moreover it has been shown that the absence of central asymmetry is related to speech perception difficulties. For example, Bellis, Trent, and Kraus (2000) showed that a population with larger neurophysiological response amplitudes (N1-P1 complex) over the left temporal lobe than over the right one were better at syllable discrimination tasks than participants showing symmetrical neurophysiological response amplitudes across both hemispheres. Considering the fact that in our study participants with strong suppressions in the right ear had better behavioral performances than less lateralized participants, it might be that asymmetry of the language function in the cortex could explain our observations. In our study all participants were strongly right-handed (more than 80% according to the Edinburgh test) so they should also be left-hemisphere dominant for the language function (Pujol et al., 1999). It could be that participants having clear lateralization of the MOCB (good reverse speech performers) have stronger connections between language areas in the cortex than poorly lateralized participants. Therefore our task may not have directly involved the MOCB but have been more dependent on general cortical lateralization. In order to test this point further research is needed to explore the link between general cortical asymmetry and that observed for the MOCB.

To conclude, we have clearly demonstrated a correlation between the degree of suppression by the MOCB and speech restoration performance. This is the first study showing that the MOCB could be implicated in time-reversed speech restoration and more generally in a paradigm that does not involve noise as a degradation. However we have to keep in mind that such an effect could be due to a more global lateralization of the system underlying speech comprehension. Moreover, the word superiority effect we observed suggests that anatomical differences can, in normal-hearing individuals, be compensated by acquired linguistic representations. In this case, though the signal analysis *per se* might be poorer in certain individuals, their knowledge of words could compensate for this perceptual weakness and so all individuals could perform similarly. This observation constitutes an interesting example of how linguistic knowledge can compensate for perceptual mechanisms.

We need further experiments with fMRI studies to test this difference in high level performances across participants and to investigate the involvement of several cerebral areas, including the auditory areas, in language processing. Better characterizing the real-time interplay between low-level auditory processes and high-level linguistic knowledge during the processing of speech is of great interest both theoretically and therapeutically.

Acknowledgments

The authors would like to thank three anonymous reviewers, Barbara Davis and Karla McGregor for their very productive comments on preliminary versions of the manuscript. The authors are very grateful for financial support of this project: the study was funded by a grant from the Rhône-Alpes region attributed to the last author and, the first author's doctoral work was funded by a grant from the *Délégation Générale pour l'Armement* (DGA) and the second author's post-doctoral funding was obtained from the GDR CNRS 2213.

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Table 1

Equivalent Attenuation in Both Ears and Asymmetry Index in the Two Groups

	EA Right ear		EA Left ear		Asymmetry Index	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
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
F value	15.32		1.73		5.37	
p value	= 0.001		= 0.2 (n.s)		< 0.05	

Note: The Table shows the mean and the standard deviation of Equivalent Attenuation (EA expressed in dB) in the right and left ears respectively, for each group of participants. The last column indicates the Asymmetry Index (difference in EA between right and left ears). The table also gives statistical differences between the two groups (*F* and p values from the ANOVAs).

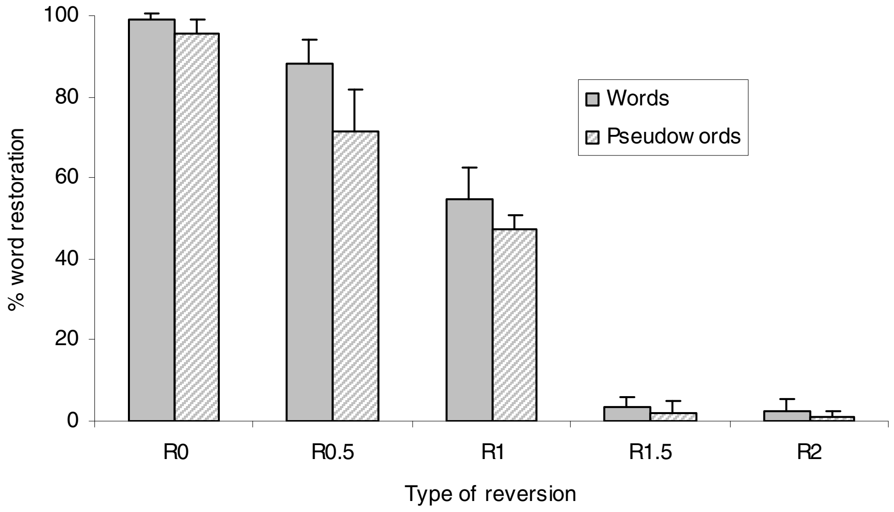
Figure Captions

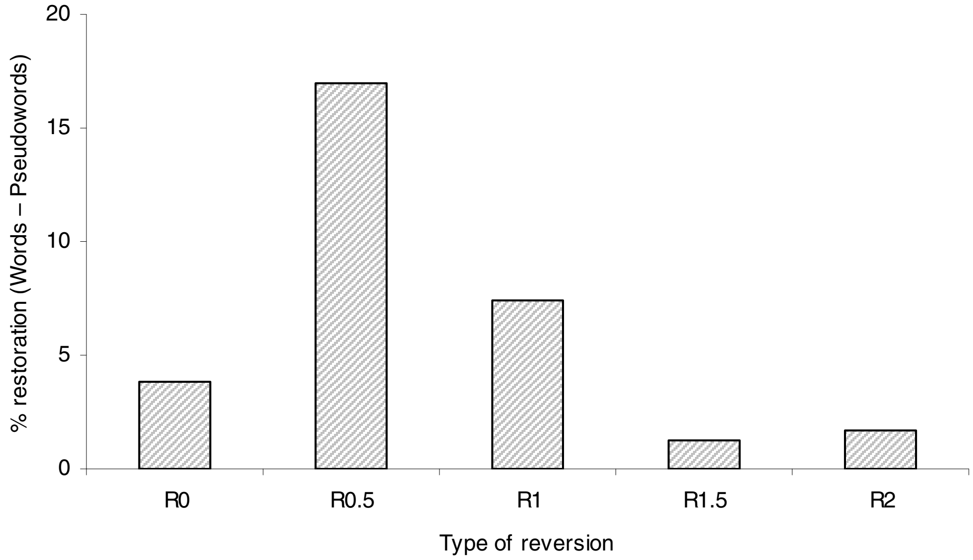
Figure 1. Rate of restoration for words and pseudowords plotted against the degree of reversion.

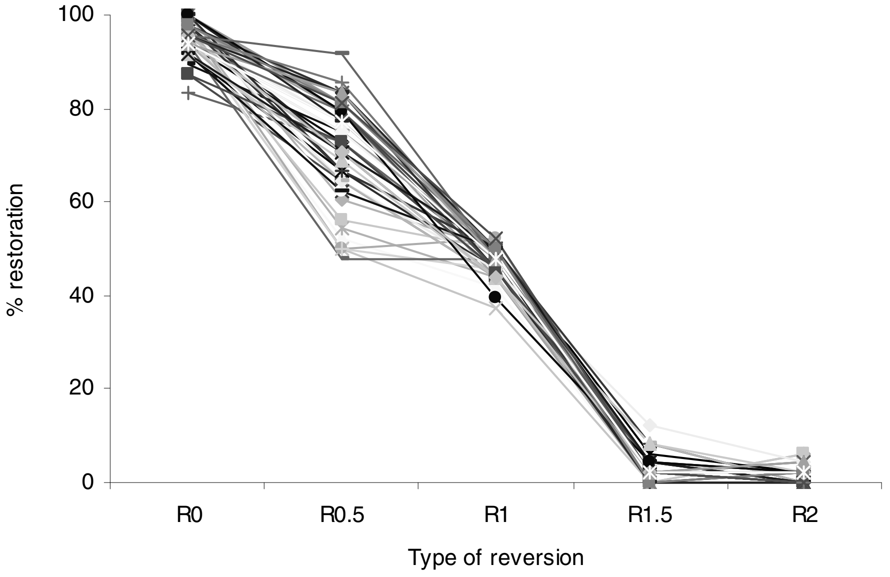
Figure2. Lexical effect in word restoration : % of restoration for Words minus % of restoration for Pseudowords.

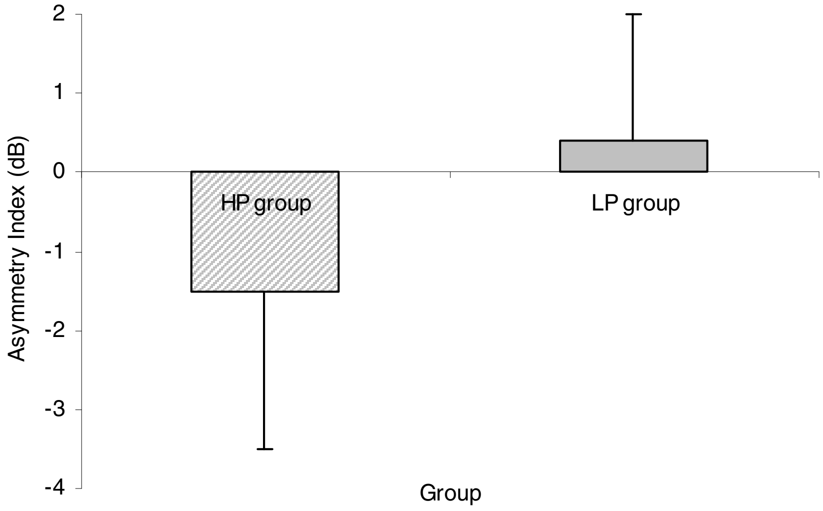
Figure 3. Time-reversed restoration of pseudowords. Each curve represents the results of one subject.

Figure 4. Asymmetry Index (in dB) for the two groups of participants


% word restoration
100
80
60
40
20
0
Words
Pseudow ords
R0
R0.5
R1
R1.5
R2
Type of reversion


20
15
10
5
0
% restoration (Words – Pseudowords)
R0
R0.5
R1
R1.5
R2
Type of reversion


100
80
60
40
20
0
% restoration
R0
R0.5
R1
R1.5
R2
Type of reversion


2
1
0
-1
-2
-3
-4
Asymmetry Index (dB)
HP group
LP group
Group