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Sensory-motor relationships in speech production in post-lingually deaf cochlear-implanted adults and normal-hearing seniors: Evidence from phonetic convergence and speech imitation

Lucie Scarbel[a,*], Denis Beautemps[a], Jean-Luc Schwartz[a], Marc Sato[b]

[a] GIPSA-LAB, Département Parole & Cognition, CNRS & Grenoble Université, Grenoble, France
[b] Laboratoire Parole & Langage, CNRS & Aix-Marseille Université, Aix-en-Provence, France

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ABSTRACT

Speech communication can be viewed as an interactive process involving a functional coupling between sensory and motor systems. One striking example comes from phonetic convergence, when speakers automatically tend to mimic their interlocutor's speech during communicative interaction. The goal of this study was to investigate sensory-motor linkage in speech production in postlingually deaf cochlear implanted participants and normal hearing elderly adults through phonetic convergence and imitation. To this aim, two vowel production tasks, with or without instruction to imitate an acoustic vowel, were proposed to three groups of young adults with normal hearing, elderly adults with normal hearing and post-lingually deaf cochlear-implanted patients. Measure of the deviation of each participant's f_0 from their own mean f_0 was measured to evaluate the ability to converge to each acoustic target.

Results: showed that cochlear-implanted participants have the ability to converge to an acoustic target, both intentionally and unintentionally, albeit with a lower degree than young and elderly participants with normal hearing. By providing evidence for phonetic convergence and speech imitation, these results suggest that, as in young adults, perceptuo-motor relationships are efficient in elderly adults with normal hearing and that cochlear-implanted adults recovered significant perceptuo-motor abilities following cochlear implantation.

1. Introduction

1.1. Sensory-motor interactions in speech perception and speech production

In the speech communication domain, an old and fundamental debate concerns the nature of processes and representations involved in speech perception and production. Concerning speech perception, auditory theories assume that speech perceptual processing and categorization are based on acoustic features and auditory representations (Stevens and Blumstein, 1978; Blumstein and Stevens, 1979; Lindblom and Maddieson, 1988; Lindblom, 1990). Conversely, the motor theory of speech perception (Liberman and Mattingly, 1985) or the direct realist theory (Fowler, 1986) respectively claim that speech perception involves the recovery of the speaker's motor intentions or articulatory gestures. More recently, various perceptuo-motor theories introduced syntheses of arguments by tenants of both auditory and motor theories, and proposed that implicit motor knowledge and motor representations are used in relationship with auditory representations and processes to elaborate phonetic decisions (Skipper et al., 2007; Schwartz et al., 2012). These theories capitalize on the increasing amount of evidence for the role of motor representations and processes in speech perception (see a recent review in Skipper et al. (2016)).

Concerning speech production, various theories have also been introduced to characterize the speaker's goals. Motor or articulatory theories, like Task dynamics (Saltzman, 1986) and the associated Articulatory Phonology (Browman and Goldstein, 1992), consider that speech targets are defined in the articulatory space. On the contrary, auditory theories like Stevens' Quantal Theory (Stevens, 1972, 1989) and Perkell's speech production control model (Perkell et al., 1995, 2000), suggest that targets are specified in auditory terms. Finally, sensory-motor models claim that speech production control is multimodal and combines auditory and somatosensory information (see Perrier, 2005; and the DIVA model, Guenther et al., 1998; Guenther and Vladusich, 2012). A number of data about the effect of auditory (e.g. Lametti et al., 2014; Shiller and Rochon, 2014) or somatosensory (Tremblay et al., 2003) perturbations applied to speech production in adults or children are in agreement with this sensory-motor framework.

From a number of these theories, sensory-motor relationships seem

* Correspondence to: GIPSA-LAB, UMR CNRS 5216, Grenoble Université, Domaine Universitaire, BP 46, 38402 Saint Martin d'Hères, France.
E-mail address: lucie.scarbel@gipsa-lab.grenoble-inp.fr (L. Scarbel).

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to play an important role in both speech perception and speech production in normal conditions. The present study deals with subjects for which some degradation of the sensory-motor link could be expected, because of sensory deficits. The first and primary situation is the case of post-lingually deaf subjects equipped with cochlear implants. Indeed, post-lingually deaf subjects are expected to have acquired efficient sensory-motor relationships before deafness. Their ability to achieve intelligible speech production is interpreted as evidence that they have maintained a stable and rather accurate internal model of these sensory-motor relationships all along their deafness life (Perkell et al., 2000). Cochlear implantation then results in providing them with a new kind of auditory input, quite different from the one they had acquired before deafness considering the very special nature of cochlear-implant coding of acoustic information. The question is to know how the internal relationships between these “new” auditory inputs, the “old” ones acquired at the first stages of development, and the motor representations are established and organized, and how efficient they are.

A number of data on speech production after cochlear implantation display an increase in acoustic dispersion of vowels after a few months of implantation (e.g. Langereis et al., 1998; Lane et al., 2005; Ménard et al., 2007), suggesting that the internal model has indeed benefited from the new auditory input provided by cochlear implantation. Interestingly however, some studies explored the response to articulatory perturbation using a bite-block task (Lane et al., 2005), a robotic device displacing the jaw during speech (Nasir and Ostry, 2008) or a lip-tube task (Turgeon et al., 2015), with or without auditory feedback. Results showed that post-lingual cochlear-implanted participants (CI) are able to adapt their articulatory trajectory when it is perturbed in order to reach their auditory goals and make their production intelligible, even when the implant is turned off. Such compensatory strategies show that perceptuo-motor abilities acquired during speech acquisition in CI subjects are still at work after deafness, though the addition of auditory information provided by the cochlear-implant does result in enhanced precision and efficiency of the sensory-motor internal model. Finally, a PET-scanning study on visual speech perception in post-lingually deaf CI patients (Rouger et al., 2012) showed that after a short adaptation period with the implant, there was a decrease of the initially abnormal activity in the superior temporal sulcus, a cross-modal brain area, accompanied by a progressive reactivation of frontal premotor speech areas. This suggests that sensorimotor neuroplasticity after cochlear implantation provides a progressive reactivation of the audio-visuo-motor linkage in CI subjects.

The second situation considered in the present study is the case of elderly subjects. They are of interest for us for two reasons. The first one is the interest of assessing the consequences of the potential decline of cognitive and language abilities in relation with decline in sensory and motor accuracy on the efficiency of sensory-motor relationships. The second reason is that a number of the cochlear-implanted post-lingually deaf participants are rather old, and we considered important to include senior subjects with no severe auditory deficit as a control population. As a matter of fact, very few studies investigated perceptuo-motor relationships in elderly population. One of them shows that elderly people adapt their production in case of degraded auditory feedback (Liu et al., 2010, 2011a, 2011b). Sensorimotor neuroplasticity was also observed in elderly people, linked with age-dependent intelligibility effects mainly found in auditory and motor cortical areas (Tremblay et al., 2013; Bilodeau-Mercure et al., 2015). Taken together, these behavioral and neuro-imaging studies suggest that sensory-motor relationships are well preserved in aging.

1.2. Phonetic convergence and imitation, a paradigm for studying sensory-motor relationships in speech

Imitation is a quite widespread phenomenon in speech communication and can be viewed as a key mechanism in the acquisition of human language. In interactive situations, adult speakers tend to continuously adapt their productions to those of their interlocutor, in order to facilitate communicative exchanges. These adaptive changes in speech production can be voluntary, that is when the speaker consciously imitates his interlocutor, but also unintentional. Indeed, unintentional imitation, or phonetic convergence, that is the tendency to automatically imitate a number of acoustic-phonetic characteristics in the productions of an interacting speaker, has been displayed in various studies (see a recent collection of papers on this topic in Nguyen et al., 2013, and for recent reviews see Babel, 2009; Aubanel, 2011; Lelong, 2012). In these studies, convergence effects have been observed both in paralinguistic features, such as gestures, and in speech acoustic parameters, such as intensity, fundamental frequency f_0 or formants. These phonetic convergence effects may be related to the social component of communication, assuming that they would contribute to setting a common ground between speakers (Giles et al., 1991) and that they could be associated to the human desire of affiliation to a social group.

Interestingly however, while most reports on phonetic convergence are based on conversational exchanges in natural conditions, a few studies showed that phonetic convergence can also be observed using laboratory settings involving non-interactive situations of communication (Goldinger and Azuma, 2004; Gentilucci and Cattaneo, 2005; Delvaux and Soquet, 2007; Garnier et al., 2013; Sato et al., 2013). For example, Delvaux and Soquet (2007) obtained phonetic convergence effects during the production of auditorily presented words without interaction, and they also reported offline adaptation to the auditory targets in post-tests following stimulus exposure. These studies hence suggest that phonetic convergence is not only a matter of social attunement, but could also involve a more basic stage of continuous automatic adaptation of the speech production system to the external speech sounds environment (for a recent review, see Sato et al. (2013)).

Such an automatic adaptation mechanism requires the existence of a sensory-motor coupling process in which variations in the external environment provide sensory targets that drive motor control procedures to adapt and produce stimuli closer to these external targets. More in detail, the speaker would program motor commands to achieve an articulatory and ultimately an auditory (or more generally sensory) goal according to the linguistic message to be conveyed to the listener. Then, in the course of speech production, the speaker would compare sensory feedback to the initial sensory objective. Variations in the external environment would shift the sensory targets and accordingly result in modifications of motor commands to converge towards speech sounds in the environment. Hence, the convergence/imitation paradigm is a natural tool to study sensory-motor coupling in speech communication.

Phonetic convergence and imitation in laboratory settings can involve various kinds of acoustic features, though fundamental frequency effects seem to be larger and easier to obtain than variations in e.g. formant values (Sato et al., 2013). The present study therefore focus on convergence and imitation on f_0 variations.

1.3. f0 perception and motor control in cochlear-implanted adults and normal-hearing seniors

Past studies on pitch control in speech production by CI subjects reported higher f_0 values for CI adults than for adults with normal hearing and, more importantly, larger variations in f_0 for CI than for adults with normal hearing (e.g. Lane and Webster, 1991). Langereis et al. (1998) and Kishon-Rabin et al. (1999) also reported that while pitch production is generally altered in CI patients soon after implantation, almost normal f_0 values were observed one year post-implantation for two participants in Kishon-Rabin et al. (1999) study. Notice that technological evolutions led to important progress in the coding of pitch in cochlear implants since these studies.

Concerning speech perception, several factors appear to influence