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Research report

Motor coordination of articulators depends on the place of articulation

Maristela Sayuri Inoue-Arai [a,b], Takashi Ono [b,*], Ei-ichi Honda [c,d], Tohru Kurabayashi [d], Keiji Moriyama [b]

[a] *Japan Society for the Promotion of Science, Tokyo, Japan*
[b] *Maxillofacial Orthognathics, Graduate School, Tokyo Medical and Dental University, Tokyo, Japan*
[c] *Oral and Maxillofacial Radiology, Graduate School, University of Tokushima, Tokushima, Japan*
[d] *Oral and Maxillofacial Radiology, Graduate School, Tokyo Medical and Dental University, Tokyo, Japan*

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ABSTRACT

Although the sounds/p/and/k/are both voiceless plosives, they have different places of articulation: bilabial and velar, respectively. The purpose of this study was to determine the relationship among articulators in plosives with reference to their place of articulation. Ten healthy subjects repeated bilabial and velar plosives in synchronization with magnetic resonance scanning. Each run was measured using a gradient echo sequence. Several linear and angular variables were defined to delineate the individual movements of articulators and to determine the temporal relationships among articulators. These variables showed distinctive changes depending on the place of articulation. In addition, movement of the velum was significantly correlated with that of the lips and the anterior part of the tongue in the bilabial plosive and with the posterior part of the tongue in the velar plosive. We conclude that unitary motor coordination of articulators depends on the place of articulation.

1. Introduction

Speech is a unique human behavior that provides a field for observing functional synergies and coordinative principles [7,14,23,35,49]. Neuromuscular system activates multiple oropharyngeal structures such as the lips, tongue, velum and vocal cords by leveraging static components such as the teeth and palate to produce various sounds with considerable modification [19,32].

According to English/Japanese phoneme inventories, the sound/p/is classified as a bilabial whereas/k/as a velar though both are voiceless plosives. Contact between the upper and lower lips produced by activity of the orbicularis oris and other facial muscles is mandatory in bilabial plosives (e.g.,/p/and/b/) while contact between the posterior dorsum of the tongue and palate accompanied by activity of the intrinsic and extrinsic tongue muscles is important in velar plosives (e.g.,/k/and/g/) to build up supra-atmospheric pressure in the oral cavity. Both situations require complete velopharyngeal closure. The tongue is one of the most important elements in articulation [5]. It changes the shape with complex contraction pattern of many intrinsic and extrinsic muscles [17]. Even in a single tongue muscle different functional roles can be performed by different sets of motor units [52]. Although the chief articulators in bilabial plosives are the lips, the involvement of the tongue in articulation of bilabial plosives has been suggested [47,53]. It is assumed that the anterior part of the tongue rapidly changes its shape to form the appropriate acoustic environment in the anterior region of the oral cavity [5]. Likewise the tongue is involved as an active articulator for velar plosives. The extrinsic tongue muscles such as the styloglossus muscle and the palatoglossus muscle are instrumental for superoposterior elevation of the posterior part of the tongue to make a complete closure with the velum. Contraction of the mylohyoid muscle elevates the floor or the oral cavity assisting in raising the heavy posterior part of the tongue to produce the velar plosive [5]. In studies using local anesthesia for blockade of the infraorabital [1] and hypoglossal [8] nerves induced motor impairment of the superior orbicularis oris [1] and tongue [8] muscles, resulting in affected bilabial [1] and velar [8] plosives. The hypoglossal nerve block also affected sound that involved the tip of the tongue [8]. Thus coordinated movement among articulators should selectively occur according to the *place of articulation* (i.e., location of the constriction/occlusion). However it is still unclear whether and how such coordination among multiple articulators occurs during bilabial and velar plosives.

Many imaging techniques including videofluorography, nasoendoscopy and ultrasonography have been used for speech evaluation. However, they have methodological disadvantages such as invasiveness, radiation exposure and limited simultaneous visualization of target areas. Non-invasiveness and repeatability in the assessment of the dynamic function of multiple articulators would

* Corresponding author at: Maxillofacial Orthognathics, Graduate School, Tokyo Medical and Dental University, 1-5-45, Yushima, Bunkyo-ku, Tokyo 113-8549, Japan. Tel.: +81 3 5803 5533; fax: +81 3 5803 5533.
E-mail address: t-ono.mort@tmd.ac.jp (T. Ono).

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be beneficial for the strategic treatment of patients with complicated articulatory problems. Moreover, visualization of the entire region related to articulation may be important for feedback regarding the outcome of rehabilitation, since appropriate articulation is achieved by the integrated movement of multiple articulators. However, the entire movement of multiple articulators cannot be precisely imaged by any of imaging tools including videofluorography, nasoendoscopy and ultrasonography. Thus, other imaging techniques have been examined to achieve this goal. A sophisticated imaging technique, electromagnetic articulography, has been introduced [24,25]. This technique is capable of measuring movements of the articulatory organs inside and outside the vocal tract with excellent spatial and temporal resolutions, thus providing useful articulatory data for investigating the speech production process. However, the placement of receiver coil may induce unexpected sensory feedback from intraoral organs which in turn may produce affected articulatory movement. Furthermore, it is difficult to place the receiver coil on the deep organs, such as the upper surface of the velum and the vocal cord.

Recent magnetic resonance imaging (MRI) studies have obtained dynamic images during actual motion, including temporomandibular joint [2,12], swallowing [4,28,45] and articulatory [3,9,26,33,40] movements. However, contamination by noise (i.e., motion artifacts) is inevitable due to the large temporal resolutions of over 100 ms [2,4,9,28,40,45]. Using a modification of the method proposed by Masaki and colleagues [33], we previously reported the usefulness of MRI movie in the evaluation of speech [48]. However, the subjects were required to repeat a given sound 128 times, which may not be suitable for clinical application. Moreover, the signal/noise ratio may deteriorate due to the fluctuation of timing caused by neuromuscular fatigue. In a subsequent study, we substantially reduced the number of repetitions without compromising the temporal or spatial resolution [20].

The purpose of this study was to clarify the relationship among multiple articulators during the production of bilabial and velar plosives using MRI movie with special attention to the *place of articulation* in healthy subjects. We tested the hypothesis that motor coordination is closely coupled among articulators that are located in the adjacent region of the *place of articulation*.

2. Materials and methods

2.1. Subjects

Ten healthy adult Japanese females aged 26.8 ± 2.0 [mean ± standard deviation (SD)] years participated after giving their fully informed consent as provided in the protocol approved by the institutional ethics committee. Subjects with normal occlusion with an Angle Class I molar relationship and no missing teeth were recruited. None of the subjects was obese as judged by the body mass index (21.5 ± 2.0 kg/m^2). All subjects reported negative neurological and developmental histories and exhibited no obvious speech difficulties as judged by the experimenter. All of the experimental procedures complied with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

2.2. Study design

Custom-made circuitry was connected to a 1.5T MRI apparatus (Magnetom Vision, Siemens AG, Erlargen, Germany), which was equipped with a head and neck coil, to enable an external trigger pulse to control the timing of the scanning sequence and to provide an auditory cue for synchronization of the subject's utterance, which was recorded simultaneously (Fig. 1). Each image had a 219- × 250-mm field of view with a pixel size of 2.03 × 1.95 mm (slice thickness: 5 mm), and the matrix size was 108 × 128. After a full practice of the articulatory task, the subject repeated vowel–consonant–vowel (VCV) syllables of the bilabial (/apa/) and velar (/aka/) plosives, synchronized to the auditory cue in a modified "waltz" rhythm for 1500 ms (i.e., 0 ms for the first tone, 750 ms for the second tone and 1125 ms for the third tone: Fig. 2). We asked the subject to breathe between the repetitions of

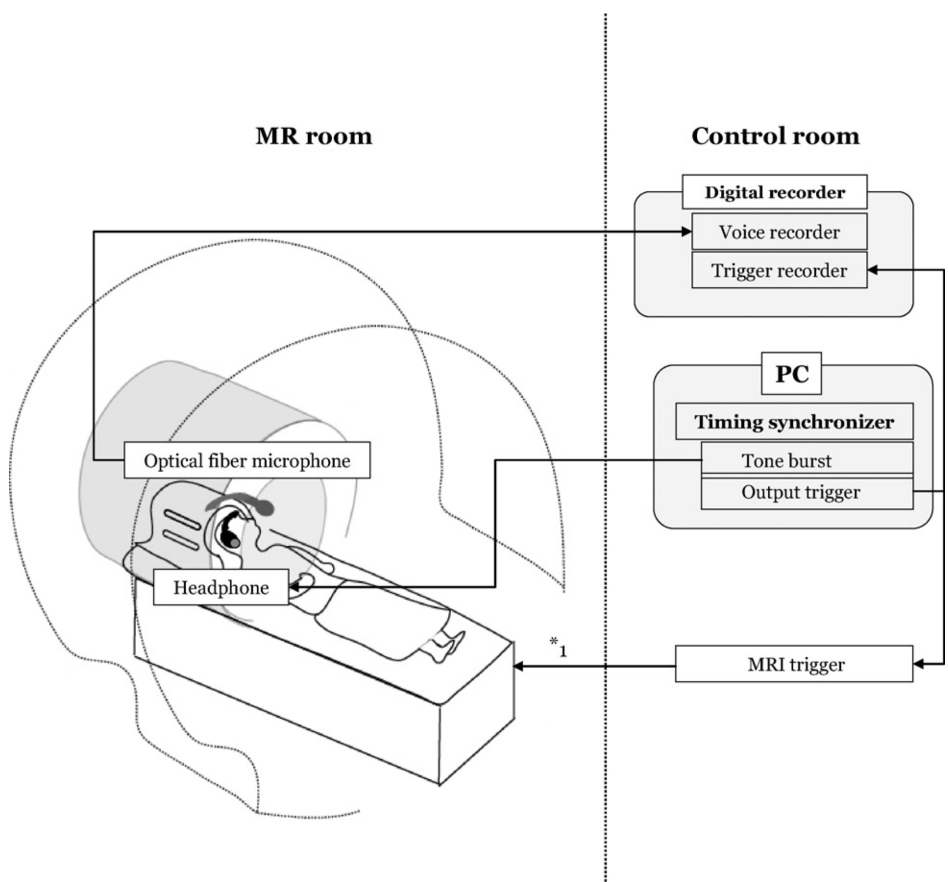

Fig. 1. Experimental set-up. An external trigger pulse to control the timing of the scanning sequence ("output trigger") and an auditory cue for the subject's utterance ("tone burst") are synchronized. Some keywords correspond to those in Fig. 2. *1: delayed 120 ms.