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Report

Somatosensory Precision in Speech Production

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Summary

Speech production is dependent on both auditory and somatosensory feedback [1–3]. Although audition may appear to be the dominant sensory modality in speech production, somatosensory information plays a role that extends from brainstem responses to cortical control [4–6]. Accordingly, the motor commands that underlie speech movements may have somatosensory as well as auditory goals [7]. Here we provide evidence that, independent of the acoustics, somatosensory information is central to achieving the precision requirements of speech movements. We were able to dissociate auditory and somatosensory feedback by using a robotic device that altered the jaw's motion path, and hence proprioception, without affecting speech acoustics. The loads were designed to target either the consonant- or vowel-related portion of an utterance because these are the major sound categories in speech. We found that, even in the absence of any effect on the acoustics, with learning subjects corrected to an equal extent for both kinds of loads. This finding suggests that there are comparable somatosensory precision requirements for both kinds of speech sounds. We provide experimental evidence that the neural control of stiffness or impedance—the resistance to displacement—provides for somatosensory precision in speech production [8–10].

Results and Discussion

The subject's task was to repeatedly produce a test word (either *row* or *straw*) while a robotic device applied a lateral load to the jaw. The loads were applied to coincide with vowel or consonant production and to thus alter somatosensory feedback during these phases of movement (Figures 1A and 1B). The loads were designed to have a destabilizing effect on the movement end points and were greatest at the two extremes. In this way, we were able to affect positioning accuracy in speech movement. Sensorimotor learning was evaluated over the course of a training period that involved several hundred utterances. Adaptation was quantified with a measure of movement curvature.

Similar Adaptation for Vowels and Consonants

Figure 1C shows a frontal plane view of jaw movement. Movements are initially straight (null field, blue); the path is deflected laterally at the beginning of training (initial exposure, red); curvature decreases with training (end-training, black); there is no after-effect following unexpected removal of the load (after-effect, green). Subjects differ in their degree of adaptation. Figure 1C shows an example of complete adaptation. Figure 1D is more typical; there is a significant decrease of curvature relative to the beginning of training, but performance never returns to the baseline level.

Adaptation was observed for both vowel- and consonant-related loads (Figure 2). For vowel-related loads, six out of seven subjects showed adaptation with the test word *straw* (Figure 2A), as indicated by a significant decrease in curvature over the course of training ($p < 0.01$). For *row*, all five subjects showed adaptation (Figure 2D). For consonant-related loads, four out of five subjects showed adaptation for *row* (Figure 2E). For *straw*, only two out of six subjects adapted to a 3 N maximum load (Figure 2B), however when the load was increased to 4.5 N maximum, four new subjects all showed significant adaptation (Figure 2C).

We assessed the amount of adaptation on a per-subject basis by computing the reduction in curvature over the course of training as a proportion of the curvature due to the introduction of a load. A value of 1.0 indicates complete adaptation. For vowel-related loads, the amount of adaptation averaged across subjects and test words was 0.46 ± 0.09 (mean $\pm$ 1 SEM). For consonants, the mean adaptation was 0.35 ± 0.05. Thus, there was comparable adaptation when loads coincided with both vowel and consonant production ($p > 0.33$). This suggests that somatosensory precision requirements are similar for both kinds of movements.

Adaptation Is Achieved through Impedance Control

We assessed the neural control strategy employed by subjects in achieving adaptation to these destabilizing force fields that had maximum effect at movement ends. We will provide three lines of evidence to suggest that subjects used impedance control to achieve adaptation.

One signature of impedance control is the absence of after-effects when the load is switched off unexpectedly. Figures 1C and 1D show examples of after-effect trials recorded at the end of training. In neither case is the movement path different from that observed under null-field conditions. A quantitative examination of after-effects shows that movement curvature during after-effect trials does not differ significantly from that observed during null-field trials ($p > 0.05$ for each of the conditions shown in Figure 3A). The curvature of after-effect trials did, however, differ from that obtained for initial-exposure trials ($p < 0.01$ in all cases). Had adaptation involved a precise remapping of neural commands to offset the external load, one would have expected a negative after-effect with a curvature comparable to that of initial-exposure trials, as is typically observed in studies of arm movement [11].

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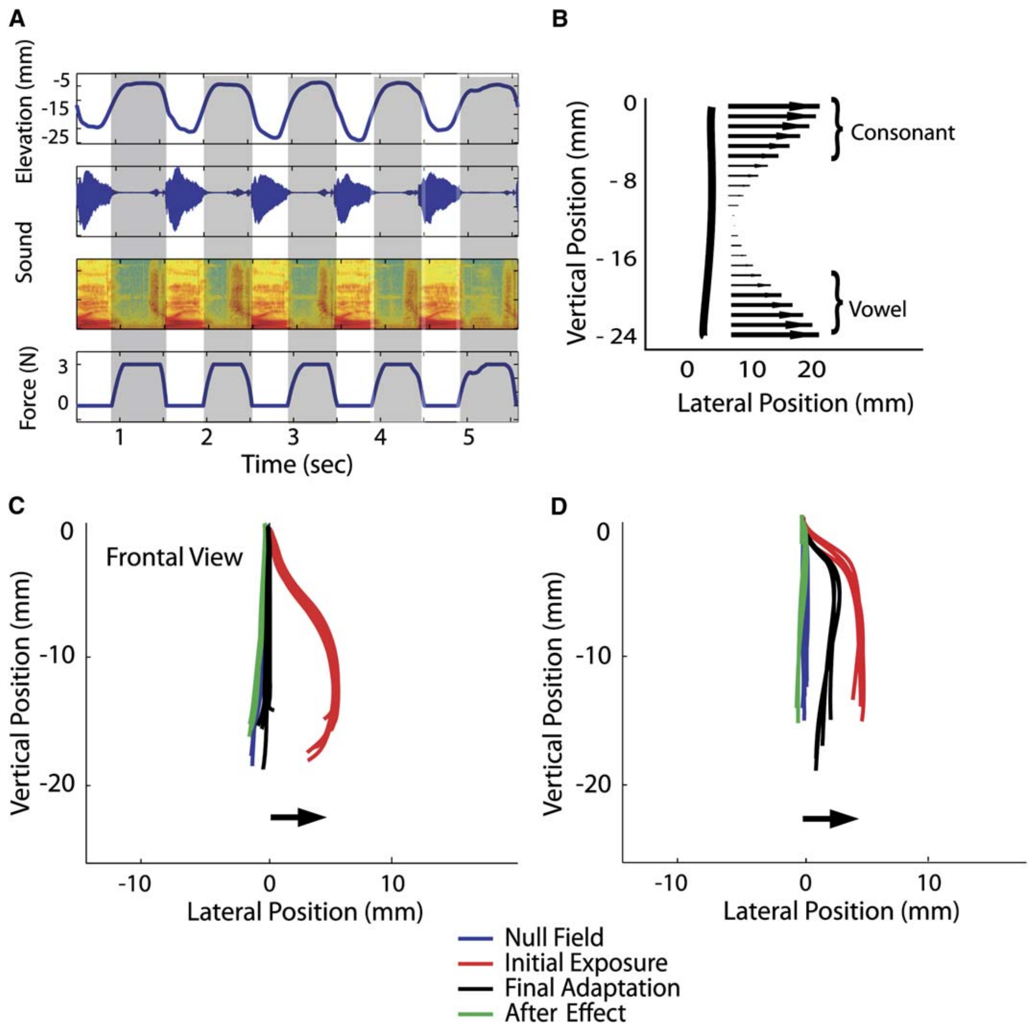

Figure 1. Forces Applied to the Jaw and Typical Patterns of Adaptation

(A) An example of force application during consonant production. The top panel shows the vertical position of the jaw during repetitions of the utterance *straw*. The second and third panels show the raw speech waveform and the corresponding sound spectrogram. The shaded area in the bottom panel shows the commanded force to the jaw. The load scales linearly with vertical jaw position and reaches a maximum when the jaw is fully closed.

(B) Frontal-plane schematic showing position dependence of the load. The load is greatest during either consonant or vowel production.

(C) Frontal view of the movement path of the jaw during the utterance *straw*. The force was applied to the jaw during vowel production. In the no-load condition, movements are straight (blue). When the load is introduced, the jaw path deviates to the right (red). With training, adaptation is achieved (black). When the load is switched off unexpectedly at the end of training, the movement paths do not show an after-effect (green).

(D) An example of imperfect adaptation. Black arrows indicate the direction of the applied load.

We directly tested the idea that subjects use impedance control to achieve adaptation. We tested four new subjects for whom, after adaptation, the direction of the force field was reversed unexpectedly rather than switched off completely. We reasoned that if an impedance based control strategy was being employed to achieve adaptation, then subjects' performance after force-field reversal would not differ from that observed at the end of training. Figure 3B shows a frontal view of performance under these conditions. The test word was *straw*, and the load was applied during the vowel. Null-field conditions are in blue. A large lateral deflection is observed with the introduction of load (red); substantial adaptation occurs after training (black). When the direction of the load is unexpectedly reversed, the movement path is a mirror image of that observed at the end of training (cyan).

Performance in this reversal test was assessed with ANOVA. Figure 3C shows significant adaptation to load by all but one subject ($p < 0.01$). Consistent with the idea that adaptation under these conditions is based on impedance control, movement curvature during the force-field reversal trials did not differ from that observed at the end of training ($p > 0.05$ for all subjects).

We quantified impedance over the course of learning for each of our subjects and for both test words (see Experimental Procedures). Figure 3D shows patterns of impedance and associated movement curvature pooled over subjects, test words, and vowel- versus consonant-related loads. Movement curvature is low under