Supplemental Data

Somatosensory Precision in Speech Production

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Supplemental Results

Comparable Kinematic Variability for Vowels and Consonants

The extremes of jaw position during opening or closing were used to compute the variability of the vowel- or consonant-related utterance. We calculated two measures of jaw variability on a per-subject basis: The first was variability relative to the mean jaw position at maximum opening or maximum closing, and the second was the coefficient of variation (CV), which is the standard deviation of jaw position divided by the mean jaw position.

We conducted tests of variability to determine the extent to which variation in jaw position during vowel and consonant production was related to the observed adaptation patterns [S1]. Jaw position differs during vowel and consonant production. Figure S1A shows a representative sample of jaw positions in the frontal plane during repetitions of the word *straw*. The figure gives jaw position during consonant and vowel production. As can be seen, jaw positions during the consonant phase are more tightly clustered than during vowel production. Figure S1B shows a box-plot for the utterance *straw* of jaw position across subjects. Figures S1C and S1D show box plots of variability and of the coefficient of variation (CV) for the same utterance. For jaw position, Tukey tests in conjunction with ANOVA showed reliable differences in vertical jaw position between vowels and consonants for both *straw* and *row* ($p < 0.01$). No differences were observed for lateral or horizontal jaw position. Variability in jaw position showed a similar pattern, where in the vertical direction reliable differences in variation were observed between vowels and consonants for both test words ($p < 0.01$).

We also tested for differences by using the coefficient of variation. The rationale for using this measure was that in many biological signals variability is proportional to amplitude [S2, S3]. That is, larger measures are naturally more variable. The coefficient of variation normalizes variability with respect to amplitude and hence enables one to test whether differences in variability in vowels and consonants are any greater than would be expected on the basis of differences in movement amplitude alone. In this case, using the coefficient of variation, we found no reliable differences in variability between vowels and consonants for either of the test words. Note that the coefficient of variation provides a rather crude normalization in that variability is simply linearly adjusted for differences in amplitude. Nevertheless, even this simple correction is sufficient to account for differences in kinematic variability between vowels and consonants.

Each of these tests was repeated on a per-subject basis. ANOVA was used to test for differences in position. Barlett's test of homogeneity of variance was used to assess differences in variability. Within-subject tests showed patterns that were comparable to those observed with between-subjects analyses.

Supplemental Acoustical Analysis

We performed a repeated-measures ANOVA on a per-subject basis as a more sensitive test of possible acoustical effects. In these analyses, only one out of 24 subjects (consonant-straw and high-force conditions) for whom acoustical data were available showed a reliable statistical effect of the introduction of load ($p < 0.01$). For five subjects (one vowel-straw, two vowel-row, and two consonant-row), individual spectral measures at the end of training were significantly different from either the null-field values or those obtained upon initial exposure to the load.

Correlation between Acoustical Measures and Movement Curvature

A characteristic of the data reported here is that subjects typically compensate only partially for the application of a load. Moreover, for those few subjects who showed any acoustical effects, these occurred at the end of training. These two observations led us to consider the possibility that effects on acoustical measures might be related to the extent of the compensation that we have seen kinematically. We assessed the relationship between kinematic measures and acoustics by computing the correlation coefficient between movement curvature and each of the first-formant, second-formant, third-formant, and centroid frequencies separately. Figure S2 shows the mean correlation between curvature and first-formant frequency during vowel production for both *straw* and *row*. The correlation is computed as a function of the separation in blocks between the curvature and acoustical measures. Each time series contained 20 blocks consisting of one null-field block and the first 19 force-field blocks. The mean value in each block was used in the analysis. An examination of Figure S2 shows that the mean correlation ranges from −0.3–0.3 and that there is no prominent peak, suggesting that movement curvature and first-formant frequency are effectively uncorrelated. Similar calculations for the other acoustical measures produced comparable results.

Supplemental Experimental Procedures

Experimental Setup and Data Acquisition

A computer-controlled robotic device (Phantom Premium 1.0, Sensable Technologies, Woburn, MA) was used to deliver a lateral load to the lower jaw. The robotic device was connected to a custom-made acrylic-metal dental appliance via a magnesium-titanium rotary connector that offered fully unconstrained movement of the lower jaw. The dental appliance was attached to the buccal surface of the mandibular teeth with a dental adhesive (Iso-Dent, Ellman International, Hewlett, NY). A force/torque sensor (ATI Nano-17, ATI Industrial Automation, Apex, NC) was mounted at the tip of the robotic device to measure the restoring force applied by the subjects in opposition to the load.

The subject's head was restrained during the experiments by connection of a second dental appliance that was glued to the maxillary teeth to an external frame consisting of a set of articulated metal arms. In the control study, subjects wore an inflatable O-ring that was connected to a similar external frame. The metal arms were locked in place for the entire experimental session.

Jaw movement was recorded in three dimensions at a rate of 1 KHz, and the three-dimensional jaw restoring force was recorded by the force/torque sensor at the same rate. The data were digitally low-pass filtered at 15 Hz. The acoustical signal was low-pass analogue filtered at 22 KHz and digitally sampled at 44 KHz.

Supplemental References

S1. Perkell, J.S., and Nelson, W.L. (1985). Varibility in production of the vowels /i/ and /a/. J. Acoust. Soc. Am. *77*, 1889–1895.

S2. Fitts, P.M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. J. Exp. Psychol. *47*, 381–391.

S3. Harris, C.M., and Wolpert, D.M. (1998). Signal-dependent noise determines motor planning. Nature *394*, 780–784.

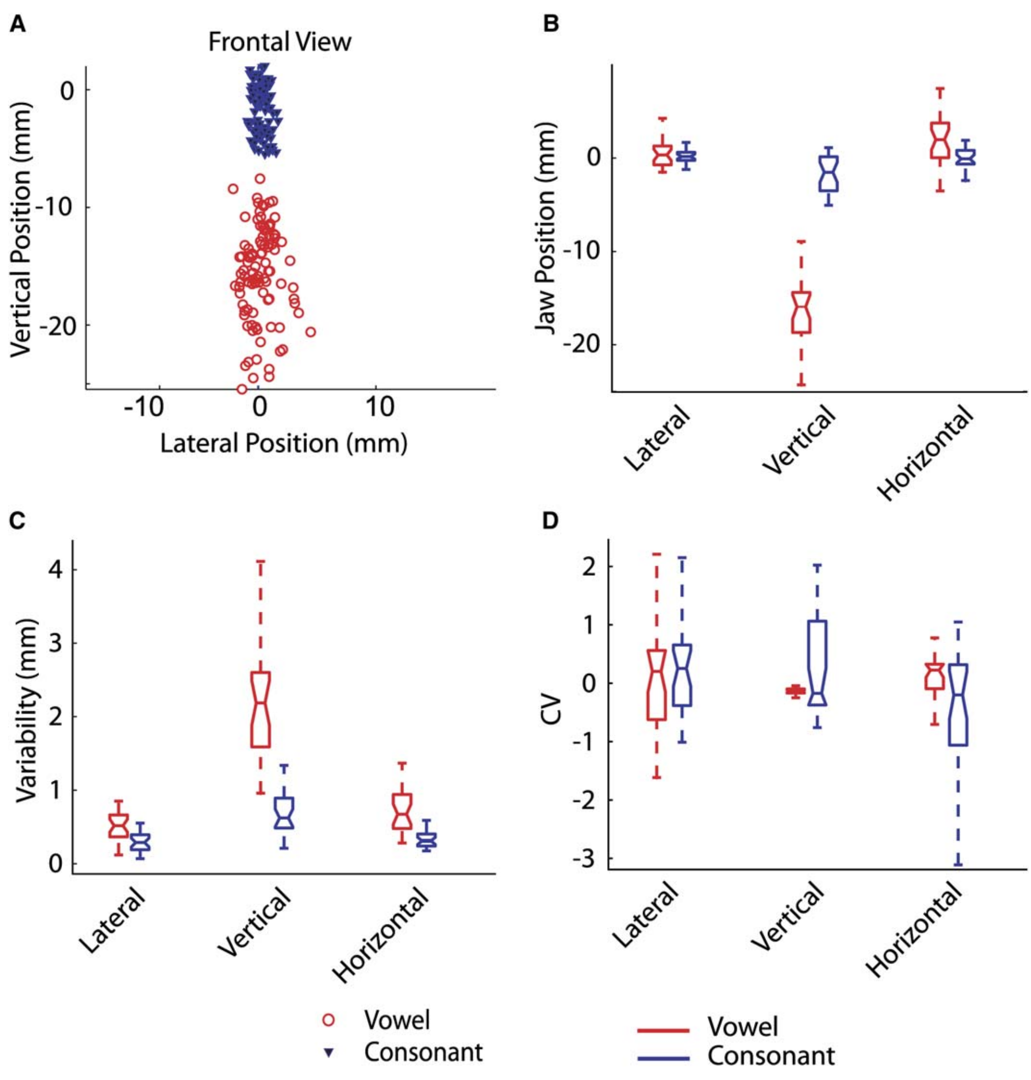

Figure S1. Variability of Jaw Position during Vowel and Consonant Production

(A) Frontal-plane view of jaw position during the production of consonants (filled triangles) and vowels (circles) for the utterance *straw.*

(B) Mean jaw position across subjects during the production of consonants and vowels for the utterance *straw*.

(C) Variability in jaw position across subjects.

(D) Coefficient of variation (CV) during the production of consonants and vowels. CV is a measure of normalized variation. Once differences in variability due to differences in movement amplitude are accounted for, differences in kinematic variability are eliminated.

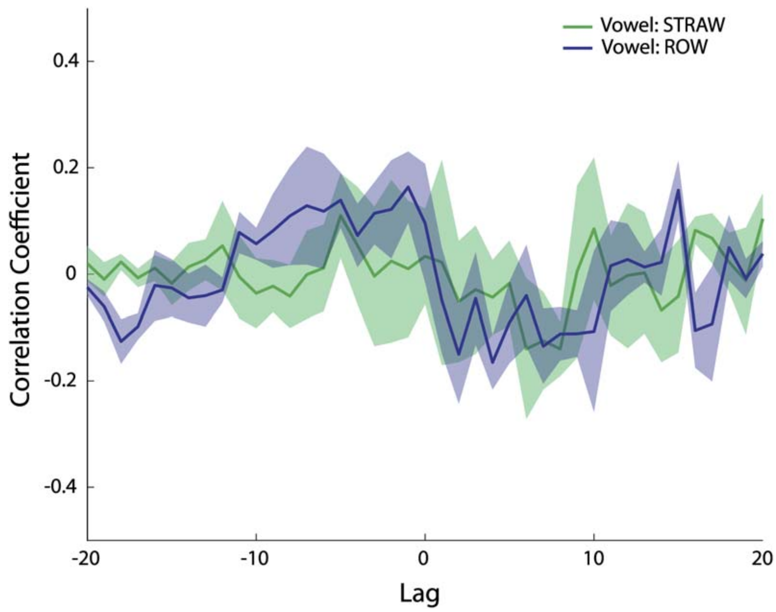

Figure S2. Correlation between Movement Curvature and First-Formant Frequency

Mean correlation coefficient (±1 SEM) between movement curvature and F1 frequency for *straw* (green) and *row* (blue). The correlation is shown as a function of the lag in blocks of trials.