Speech Motor Adaptation Without Auditory Feedback

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Abstract

The nervous system receives both auditory and somatosensory information while we talk. Speech production entails sensorimotor control and as such relies on multiple sensory inputs. The role of somatosensory input in speech motor control is little understood. Previous studies seeking to identify a somatosensory basis to speech motor function have done so in the presence of auditory inputs. Hence any effects that were observed there could be attributed to the presence of the auditory signal. Here we show that somatosensory input on its own may underlie speech production and speech motor learning. This is done by studying speech learning in cochlear implant recipients, tested with their implants turned off. Speech motor learning was assessed using a robotic device that applied forces and thus displaced the jaw and altered somatosensory feedback during speech. We found that with training implant subjects gradually adapted to the mechanical perturbation. The observed corrections were for movement deviations that were rather small, in the range of a few millimetres. This indicates that speakers have precise somatosensory expectations independent of auditory goals.

1. Introduction

One of the puzzles of human language is that individuals who become deaf as adults remain capable of producing quite intelligible speech for many years, in the absence of auditory input [1]. This ability suggests that speech production is substantially dependent on non-auditory sensory information, and in particular, input from the somatosensory system. Previous experimental studies exploring the somatosensory basis of speech control were carried out in the presence of auditory inputs [2-5]. Hence, any effects that were observed previously may due to the presence of the auditory signal. Here we demonstrate that somatosensory input has independent contributions to speech production and speech motor learning. For this, speech learning was studied in cochlear implant recipients who were tested with their implants turned off. A robotic device displaced the jaw and thus altered somatosensory feedback during speech. Even in the absence of auditory input, implant subjects progressively corrected their speech movements to offset errors in the motion path of the jaw. Indeed, the levels of adaptation that we observed were comparable for implant subjects and normal hearing control subjects. This indicates that speech learning is substantially dependent on somatosensory feedback. Speech production should be understood both as an auditory [7, 8] and a somatosensory task [4-6]. This finding of a somatosensory goal during speech among deaf speakers may help explain the intelligibility of their speech. A fuller version of this report can be found in reference [6].

2. Speech motor adaptation

Five post-lingually deaf adults took part in the study [6]. The hearing-impaired subjects had profound

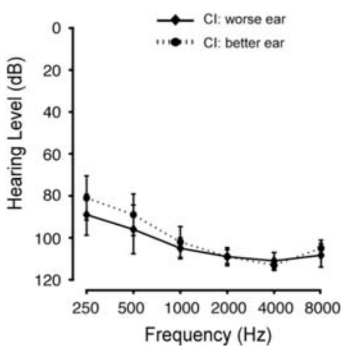

Figure 1. Implant subjects' hearing level.

hearing loss in both ears (Figure 1). Another six age-matched control subjects participating in the study had hearing level typical of their age range. During the experimental session, a robotic device applied a mechanical load to jaw as the subject repeated aloud

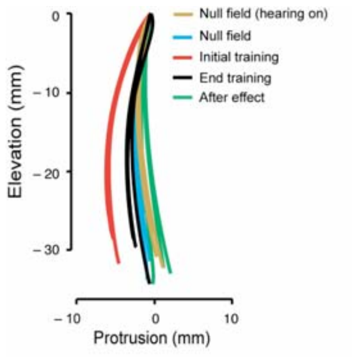

Figure 2. Jaw movement paths of an implant subject.

test-utterances that were selected randomly from a set of four (*saw*, *say*, *sass*, *sane*). A velocity-dependent mechanical load acted to displace the jaw in a protrusion direction, altering somatosensory feedback. Subjects were trained over the course of several hundred utterances. Sensorimotor learning was evaluated using a measure of movement curvature to quantify adaptation. The hearing-impaired subjects were trained with their implant turned off, while control subjects had full hearing during training.

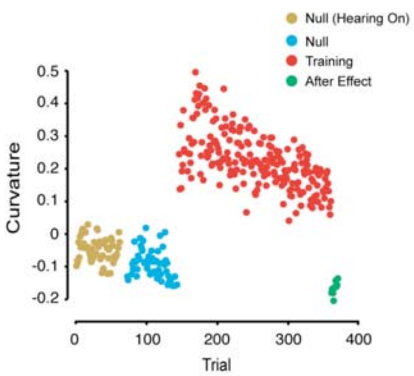

Figure 3. Learning curve for an implant subject.

We found that with training subjects corrected for the loads, such that the motion path approached that normally experienced under no-load conditions. Figure 2 shows a sagittal plane view of representative jaw trajectories in speech for an implant subject. Movements are straight in the absence of load (null condition: cyan); the jaw is displaced in a protrusion direction when the load is first applied (initial-exposure: red); curvature decreases with training (end-training: black); there is a small after-effect following unexpected removal of load (after-effect: green). Movements for the implant subject under no load conditions are similar regardless of whether the implant is on or off (implant-on: gold, implant-off: blue). Figure 3 shows movement curvature measures for an implant subject for individual trials over the entire course of the experiment. As in the movements shown in Figure 2, values of curvature were low in the null condition, increased with the introduction of load and then gradually decreased with training. In the implant group, adaptation was observed in all five subjects ($p < 0.01$ for all subjects). Thus even in the absence of auditory feedback, somatosensory input mediates speech movements in post-lingually deaf adults. Only four of six control subjects adapted to the load. The levels of adaptation that we observed were comparable for implant subjects and normal hearing control subjects. This further suggests a prominent role for somatosensory feedback in individuals with hearing loss.

3. Acoustical effects

In individuals with normal hearing, the adaptation observed in this study could have been driven by somatosensory or auditory feedback, or the two in combination: somatosensory feedback is altered because the load alters the movement path of the jaw and changes somatosensory input; auditory feedback may also change because the load might affect speech acoustics by altering the shape of the vocal tract. Since subjects in the implant group adapted with the implant turned-off, auditory input does not seem to be necessary for speech learning, at least in post-lingually deaf adults. In order to evaluate the presence of auditory cues for adaptation that might have been used by the normal hearing control subjects, acoustical changes in the speech signal were assessed over the course of training. Acoustical effects related to the application of load were evaluated by computing the first and second formant frequencies of the first vowel in each of the test-utterances. For both groups, no significant differences were observed in any of the vowel formants as the load was introduced and nor were there any differences in the formant values over the course of training ($p > 0.05$). This further implies that auditory feedback played little role in mediating the observed adaptation.

4. Kinematic and acoustical precision

The adaptation seen in implant subjects may have been due in part to changes in somatosensory and / or kinematic precision that took place in response to compensate for the auditory loss. As already noted, all of our implant subjects showed statistically reliable adaptation whereas only two-thirds of the normal hearing control subjects (4 out of 6) had similar patterns.

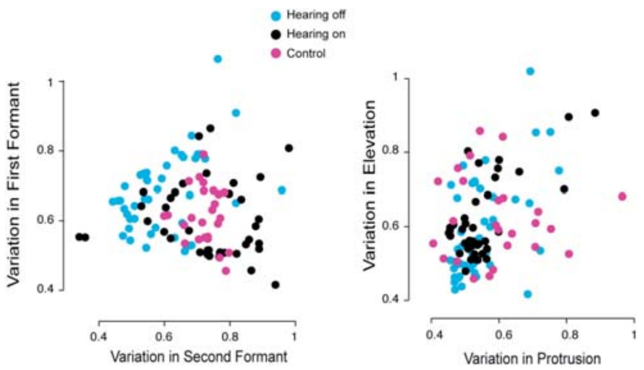

Figure 4. Acoustical and kinematic precision for implant and control subjects.

We looked for differences in the kinematic and acoustical characteristics of the two groups under null conditions. We examined the first two formants and associated values of jaw protrusion and elevation. We assessed possible differences between implant and control subjects in acoustical and kinematic precision by computing their respective coefficients of variation (CV), which are measures of variability normalized by the mean. Figure 4 plots the CVs of the first two formants and the CVs of protrusion and elevation. The individual data points give null condition values of the CV for each utterance and each subject separately. No differences in CV between implant and control subjects were found for either of the acoustical or kinematical parameters ($p > 0.05$). This suggests that on average the implant group is no more sensitive to somatosensory change than subjects with normal hearing. This finding further underscores the reliance on somatosensory feedback in speech production.

5. Implications on sensory integration and speech motor control

The adaptation shown by the implant group may reflect a heightened sensitivity to somatosensory input as a consequence of hearing loss but it might also reflect the normal role of somatosensory inputs in determining speech movements. Our data provide some support for both possibilities. The fact that the compensation observed here is similar for implant and control subjects suggests that the implant group is no more sensitive to somatosensory change than subjects with normal hearing. However, all subjects in the implant group show adaptation in comparison to the more typical 2/3 proportion in the control group [4-5]. This difference would argue in favour of the idea that somatosensory sensitivity is improved in at least some individuals with late-onset hearing loss.

The degree to which subjects compensate for load is comparable in implant subjects and in age-matched controls. Adaptation was incomplete in both cases; on average there is about a 20% reduction in movement error over the course of training. However, partial adaptation is typical of studies of speech motor learning, both with mechanical loads and altered acoustical feedback [4-5, 8] and may reflect the imprecision of articulatory targets and the possibility for inter-articulator trade-offs in the achievement of auditory goals.

The present finding that implant and control subjects achieved a comparable level of adaptation, bears on multisensory integration in speech. Speech production typically involves integration of auditory and somatosensory inputs. In subjects with normal hearing, inputs from each modality contribute to the error information that drives adaptation. The simplest possibility is that the nervous system linearly sums error information to achieve a composite measure of total sensory error [9-10]. For implant subjects, particularly in the context of the present experiment, where testing occurs shortly after the implant is turned off, we see that subjects can rapidly place reliance on somatosensory input to achieve adaptation and can seemingly discount the auditory channel. The weighting of sensory inputs is not fixed and indeed it seems possible to quickly alter the weighting if needed.

References

[1] R. Cowie, R. E. Douglas-Cowie & A. G. Kerr. A study of speech deterioration in post-lingually deafened adults. *J. Laryngol. Otol.* **96**, 101-112 (1982).
[2] B. Lindblom, J. Lubker & T. Gay. Formant frequencies of some fixed-mandible vowels and a model of speech motor programming by predictive simulation. J. Phonet. **7**, 147–161 (1979).
[3] J. H. Abbs & V. L. Gracco. Sensorimotor actions in the control of multi-movement speech gestures. *Trends Neurosci.* **6**, 391-395 (1983).
[4] S. Tremblay, D. M. Shiller & D. J. Ostry. Somatosensory basis of speech production. *Nature* **423**, 866-869 (2003).
[5] S. M. Nasir & D. J. Ostry. Somatosensory precision in speech production. *Curr. Biol.* **16**, 1918-1923 (2006).
[6] S. M. Nasir & D. J. Ostry. Speech motor learning in profoundly deaf adults. *Nature Neurosci.* **11**, 1217-22 (2008).
[7] J. F. Houde & F. M. Jordan. Sensorimotor adaptation in speech production. *Science* **279**, 1213-1216 (1998).
[8] Jones, J. A. & Munhall, K. G. Remapping auditory-motor representations in voice production. *Curr. Biol.* **15**, 1768-1772 (2005).
[9] M. O. Ernst & M. S. Banks. Humans integrate visual and haptic information in a statistically optimal fashion. *Nature* **415**, 429-433 (2002).
[10] S. J. Sober & P. N. Sabes. Multisensory integration during motor planning. *J. Neurosci.* **23**, 6982-6992 (2003).