Proceedings of Meetings on Acoustics

ICA 2013 Montreal
Montreal, Canada
2 - 7 June 2013

Speech Communication
Session 2aSC: Linking Perception and Production (Poster Session)

2aSC55.   Speech sensorimotor learning through a virtual vocal tract

Jeffrey J. Berry*, Cassandra North, Benjamin Meyers and Michael T. Johnson

 *Corresponding author's address: Speech Pathology & Audiology, Marquette University, Milwaukee, WI 53201-1881, jeffrey.berry@marquette.edu

  Studies of speech sensorimotor learning often manipulate auditory feedback by modifying isolated acoustic parameters such as formant frequency or fundamental frequency using near real-time resynthesis of a participant's speech. An alternative approach is to engage a participant in a total remapping of the sensorimotor working space using a virtual vocal tract. To support this approach for studying speech sensorimotor learning we have developed a system to control an articulatory synthesizer using electromagnetic articulography data. Articulator movement data from the NDI Wave System are streamed to a Maeda articulatory synthesizer. The resulting synthesized speech provides auditory feedback to the participant. This approach allows the experimenter to generate novel articulatory-acoustic mappings. Moreover, the acoustic output of the synthesizer can be perturbed using acoustic resynthesis methods. Since no robust speech-acoustic signal is required from the participant, this system will allow for the study of sensorimotor learning in any individuals, even those with severe speech disorders. In the current work we present preliminary results that demonstrate that typically-functioning participants can use a virtual vocal tract to produce diphthongs within a novel articulatory-acoustic workspace. Once sufficient baseline performance is established, perturbations to auditory feedback (formant shifting) can elicit compensatory and adaptive articulatory responses.

INTRODUCTION

Broadening our understanding of the components and processes of speech sensorimotor learning is key to forwarding methods of speech neurorehabilitation. Sensorimotor adaptation (SA) is a form of short-term sensorimotor learning that does not require conscious effort (Mazzoni and Krakauer, 2006) and carries great potential for rehabilitation applications (Bastian, 2008). SA is characterized by the maintenance of a compensatory motor response to a sensory feedback perturbation after sensory feedback has been masked. Researchers have studied neurorehabilitation applications of SA for a variety of common challenges associated with brain injury. Specifically, evidence has been provided supporting approaches to the treatment of hemineglect (Pisella et al., 2006, Rossetti et al., 1998), gait (Reisman et al., 2007, Reisman et al., 2010, Bultitude et al., 2012), and upper limb movement (Subramanian et al., 2010, Lehrer et al., 2011). Several rehabilitation systems that exploit aspects of SA use virtual reality environments as patient interfaces (Laver et al., 2012). The broad objective of the current work is to bolster exploration of the potential use of SA phenomena in speech neurorehabilitation.

SA is an important focus in the study of speech (Houde and Jordan, 2002, Villacorta et al., 2007, Purcell and Munhall, 2006), but has yet to be studied in individuals with severe motor speech disorders. Speech adaptation is elicited experimentally using acoustic signal processing techniques to modify the sounds that a speaker hears herself producing. Established techniques are limited because participants are required to produce acoustically high-quality speech. This limitation has proven restricting even in the study of typical functioning talkers, since the speech of some individuals cannot be resynthesized with sufficient quality using common linear predictive coding-based approaches. Given the lack of a robust speech-acoustic that is characteristic of individuals with severe dysarthria, conventional acoustic resynthesis methods cannot be reliably implemented for the exploration of SA in dysarthria.

We have developed a novel technique for eliciting speech adaptation that does not require acoustic resynthesis of the participant's speech. An electromagnetic articulography (EMA) system (Wave Speech Research System - Northern Digital, Inc.) is used to drive an articulatory speech synthesizer. This EMA system has features that support possible clinical implementation (e.g., automated head movement correction, and no requisite calibration procedure). Moreover, with proper setup, this EMA system can achieve average sensor tracking errors below 0.5 mm for dynamic tracking with sensor velocities in the upper range typical of human speech kinematics (Berry, 2011). The robust acoustic output of the articulatory synthesizer is sent back to the participant to serve as the source of auditory feedback and can be perturbed using an established, acoustic-based method (Cai et al., 2010, Cai et al., 2011). Since no acoustic input is required from the participant, our articulatory synthesis technique can be used with any participant, regardless of individual speech-acoustic quality. This makes the technique viable for the study of speech SA in participants with motor speech disorders. Moreover, since this technique involves re-expressing a participant's articulatory movements in a novel articulatory-acoustic working space, it can be used to support more foundational scientific study of the process of learning novel speech sensorimotor transformations and furthering our understanding of feedforward and feedback mechanisms in speech motor control (Perkell, 2012). Haith and Krakauer (2012) suggest that, while the bulk of sensorimotor learning research has utilized adaptation paradigms, learning of novel sensorimotor behaviors without perturbation is characteristic of much real human experience and therefore a poignant research consideration. Several labs have studied limb sensorimotor control using virtual environments to create novel sensorimotor working spaces (e.g., Mussa-Ivaldi et al., 2011, Mosier et al., 2005, Liu et al., 2011, Nagengast et al., 2009, Sternad et al., 2011). Thus, another important potential contribution of our current line of work is in broadening the basic science of the novel learning paradigm to include the auditory-motor transformations that are important for speech motor learning.

In this paper, we present data from our first efforts in completing SA experiments using a virtual vocal tract. Participants were asked to produce diphthongs in a novel articulatory-acoustic working space using an articulatory speech synthesizer to provide participant-controlled auditory feedback. Consistent with a typical SA paradigm, following a period of "baseline" performance, auditory feedback was perturbed through systematic shifts to the first (F1) and second (F2) formant frequencies, then masked for a number of replicates before being returned to the baseline condition. Our primary interest is in gauging the potential for participants to achieve sufficient control over the virtual vocal tract during a relatively brief baseline performance in order to establish a basis for compensation and adaptation responses to auditory perturbations.

METHODS

Articulatory Resynthesis with a Virtual Vocal Tract

The NDI Wave EMA system was used to register the real time movements of a participant's tongue, lips, and jaw. Five sensors were attached along the midsagittal plane (two on the dorsal surface of the tongue, one on each lip, and one at the juncture of the central mandibular incisors near the gingival border). Reference sensors corrected for participant head movements in real time. Articulator movements were transformed into control parameters for a Maeda style software articulatory speech synthesizer (Maeda, 1982, Maeda, 1990, Huckvale, 2009). Figure 1 shows the synthesis parameters that can be manipulated through a piece-wise linear mapping from a participant's articulatory movements. The mathematical method for transforming articulator movements was speaker-independent, though speaker-specific calibrations based on differences in the available physical working space within the oral cavity were necessary. The "speech" heard by all participants was indistinguishable, except for differences in vowel quality reflecting idiosyncrasies in articulatory movement and presumably different levels of proficiency between participants in reliably controlling the synthesizer.
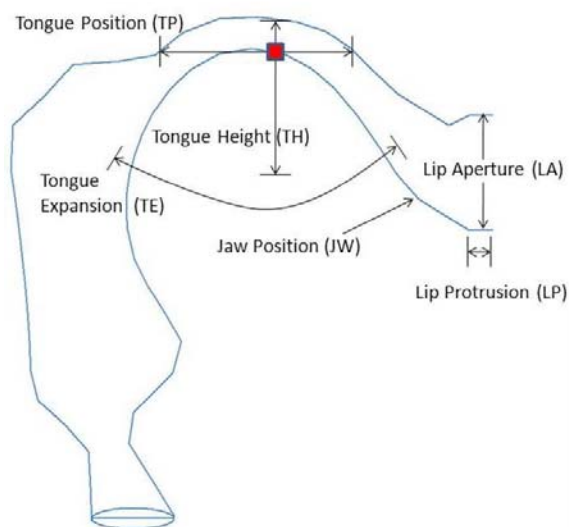
FIGURE 1. Articulatory synthesizer used as each participant's virtual vocal tract. Synthesis parameters that could be manipulated by a participant's articulatory movements are labeled.

Auditory Feedback Perturbations

Perturbations to auditory feedback were achieved with software used in previous speech SA experiments (Cai et al., 2010, Cai et al., 2011). These perturbations were designed to evoke involuntary changes in the participant's articlulator movements (Munhall et al., 2009). Each experimental run was characterized by five phases: 1) a baseline phase during which participants heard unperturbed auditory feedback from the articulatory synthesizer; 2) a ramp phase during which auditory feedback was gradually perturbed through increasing shifts in F1 and F2; 3) a full perturbation phase during which the maximum auditory feedback perturbation is maintained; 4) a masking phase, during which auditory feedback is eliminated with masking noise; and 5) a return phase during which auditory feedback is returned to the baseline condition. Thus, during an experimental run the participant established performance (baseline), was assessed for compensation to gradually increasing perturbation (ramp), was assessed for sustained compensation (full perturbation), was assessed for adaptation (masking), and then was "de-adapted" (return). The current work focused on adaptation of isolated productions of /e/ and /o/. Compensation was trained on the /e/ by gradually shifting the F1 down in frequency and F2 up in frequency (toward /i/). This acoustic shift supports the participant's perception of increasing vowel height. The precise settings for the shift were common across all participants and were established by the experimenter through trial-and-error by acoustically resynthesizing a monophthong /e/ (produced by the articulatory synthesizer) until it achieved perceptual quality and

formant patterns characteristic of /i/. Anticipated compensation and adaptation responses would be in opposition to the perceived auditory perturbation (Purcell and Munhall, 2006). In the acoustic domain this result would be indicated by an increase in F1 and a decrease in F2. The corresponding articulatory change might be a lowering of tongue height (Fant, 1970).

Participants

Five typically-functioning talkers (3 male and 2 female) were engaged in the experimental protocol. All participants (S1, S2, S3, S4, and S5) met the inclusionary criteria of being between the ages of 18-45, being native American English speakers with an upper-midwestern dialect, and having no history of speech, language, or hearing pathology, no history of orofacial surgery (other than typical dental extractions), and no history of use of anticonvulsant, antipsychotic, or anti-anxiety medications. All participants passed a brief audiometric pure-tone screening to assure typical hearing. Participants read and signed informed consent documents. All procedures and documentation were approved by the Institutional Review Board of Marquette University. Each participant received a $50 cash incentive for participating in the approximately two hour experimental process.

Procedures

EMA sensors were adhered to the articulators using Periacryl™ adhesive (Glustich Inc., Delta, BC, Canada). To improve the duration and reliability of sensor adhesion, lingual sensors were bonded with small squares of silk between the sensor and lingual surfaces. Similarly, labial sensors had 2 mm diameter circles of Super Poligrip Strips® denture wax (GlaxoSmithKline Consumer Healthcare L.P.) and the dental sensor had a 3 x 5 mm strip of Stomahesive® periostomal barrier (ConvaTec, Skillman, NJ, USA) used as intermediaries to support adhesion. Five articulatory sensors were used for each participant (central mandibular incisors, lower lip, upper lip, tongue dorsum, and tongue blade sensors were all placed approximately in the midsagittal plane).

Participants were seated in a non-metallic chair (constructed primarily of polyvinyl chloride) with the field generator for the NDI Wave EMA system positioned approximately 5 cm from the head in left profile to assure that all sensors fell within the 300mm^3 field setting of the EMA system. Participants wore a pair of plastic glasses frames with a 6DOF reference sensor attached at midline to allow for use of the EMA system's automated head movement correction algorithm. A computer screen was positioned approximately 1 m away to display the stimuli "A" and "O". Participants wore insert earphones through which pink noise was mixed with synthesizer audio feedback. Participants were instructed to use their articulators to control the speech synthesizer in sustaining the indicated vowel sound when it appeared on the screen and for as long as they could hear it. Audio gating was achieved in synchrony with visual cues using Matlab scripts in conjunction with the TransShiftMex software (Cai et al., 2010). For each trial, auditory feedback was available for 2.5 s windows with 5 s breaks between adjacent repetitions.

Following preparation, participants were given a period of accommodation to the EMA sensors, during which they spoke casually with the experimenter and lab staff and read a paragraph of text to become accustomed to the size and location of the text-prompted stimuli. Next a series of "calibration" maneuvers was recorded to define the physical limits of each participant's kinematic working space and obtain a viable mapping to the virtual vocal tract Calibration maneuvers included: exaggerated CV reps, maximum jaw wags, maximum lip protrusions and retractions, and sustained corner vowels. The mapping was determined adequate if the participant was able to achieve a reasonable approximation of the target vowel qualities within a few attempts without repeated, complete constriction of the virtual articulators. Once the calibration process was completed the adaptation experiment was initiated. The adaptation experiment required a total of 220 phoneme productions and lasted approximately 30 minutes. Table 1 outlines the experimental phases, number of replicates, targeted phonemes, and auditory feedback status.

**TABLE 1.** Adaptation experiment phases and conditions.

Phase	Target Phoneme	Total Replicates	Auditory Feedback Status
Baseline	/e/ and /o/	80	Unperturbed Artic. Synth
Ramp	/e/	40	Gradual F1 & F2 Shifts
Full Pert.	/e/	40	Constant (max) F1 & F2 Shift
Masking	/e/ and /o/	40	Noise
Return	/e/ and /o/	20	Unperturbed Artic. Synth

Acoustic Analysis

Acoustic analysis and indexing were completed using the TF32 software (Milenkovic, 2005). Formant tracks were obtained using pitch-synchronous LPC (26 coefficients). All spectrograms were analyzed with a 300 Hz bandwidth. Given the very robust signal generated by the articulatory synthesizer, formant tracking errors were rarely apparent. When such errors occurred, F1 and F2 values were manually corrected within visualized windows of approximately 500 ms and a frequency range around 5 kHz. Indices were placed around an approximately 100 ms span characterized by a steady state F1 and F2 (the off-glide in a diphthong /e/). Formant values were averaged within this window to obtain formant frequency values.

RESULTS

Figure 2 shows an example of the acoustic data for the /e/ productions obtained from one participant during different relevant phases of the SA experiment. Data are shown in an F1-F2 space with axes oriented in such a manner as to roughly mimic the articulatory working space. Black dots represent the 40 /e/ replicates during baseline performance. Red triangles are indicators of compensation, reflecting the 40 /e/ replicates during full perturbation. Green squares are indicators of adaptation, reflecting the 20 /e/ replicates during masking. Yellow triangles are the 10 /e/ replicates produced during the return phase (de-adaptation). While there is notable overlap in these data points across the various phases of the experiment, there appears to be a tendency for the participant to follow the anticipated path of acoustic change that would be characteristic of SA. Specifically, baseline values tend to assume the highest F2 values and lowest F1 values. Following the ramp stage (not shown in this figure), values from the full perturbation phase tend to move toward lower F2 and higher F1 values (note that the scale of F1 has been inverted to approximate the articulatory working space), consistent with compensation. During the masking phase, values appear to be fairly widely distributed, but may tend to be intermediate to the baseline and full perturbation values, consistent with adaptation. Finally, during the brief de-adaptation phase, the acoustic variability appears to be somewhat reduced and the formant values appear to be fairly comparable with those obtained during full perturbation, suggesting that the participant did not return completely to baseline performance.
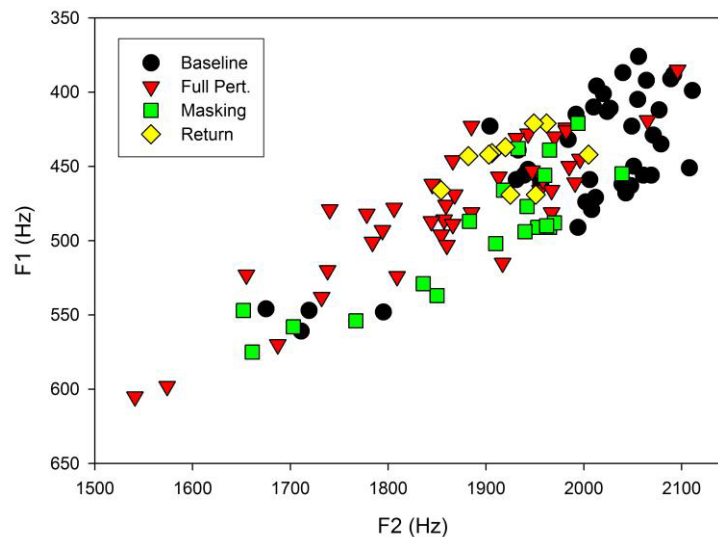
FIGURE 2. Acoustic data obtained from /e/ productions of one participant (S2). Data are coded by experimental phase (ramp phase replicates are not shown).

Figure 3 shows average acoustic data values for each participant during each experimental phase. Experimental phase is differentiated as previously by shape and color. Participant identifiers are shown in text inside each data point. A red arrow in the lower right hand corner of the figure approximates the anticipated direction of compensation and adaptation based on the perturbations used in the experiment. Despite the use of a vocal tract with the same acoustic working space, participants appear to use different acoustic ranges within the overall space.

Nonetheless, in all cases the location of average values for the full perturbation and masking stages (and even the return phase, excluding S4) appear to assume lower F2 values and higher F1 values relative to each individual's baseline performance. This observation is consistent with the interpretation that all participants compensated and adapted from baseline performance.
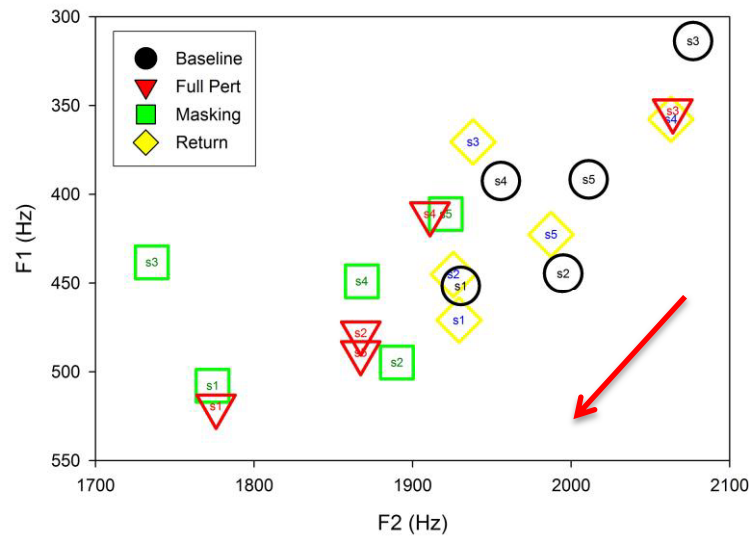
FIGURE 3. Acoustic data obtained from /e/ productions for all participants averaged across replicates within each experimental phase. Data are coded by experimental phase (ramp phase replicates are not shown) and participant identifier. The large red arrow in the lower right corner of the figure approximates the anticipated direction of compensation and adaptation.

Repeated measures ANOVA with Greenhouse-Geiser correction was used within participant to determine that mean formant values differed significantly between experimental phases for all participants (**S1:** $F_{(1.560, 60.859)} = 49.188$ $p < 0.001$ for F1, $F_{(2.052, 80.022)} = 63.480$ $p < 0.001$ for F2; **S2:** $F_{(1.697, 66.173)} = 52.730$ $p < 0.001$ for F1, $F_{(1.919, 74.832)} = 67.145$ $p < 0.001$ for F2; **S3:** $F_{(1.563, 60.958)} = 24.762$ $p < 0.001$ for F1, $F_{(2.087, 81.403)} = 88.863$ $p < 0.001$ for F2; **S4:** $F_{(1.912, 74.586)} = 61.647$ $p < 0.001$ for F1, $F_{(1.835, 71.561)} = 58.001$ $p < 0.001$ for F2; **S5:** $F_{(1.779, 69.397)} = 66.755$ $p < 0.001$ for F1, $F_{(1.904, 74.266)} = 61.489$ $p < 0.001$ for F2). Post-hoc tests using Bonferroni correction revealed that F1 values for S1 differed significantly ($p < 0.001$) between baseline and all other phases and F2 values differed significantly between baseline and all other phases ($p < 0.001$) except for baseline and full perturbation (significant at $p < 0.018$). For S2, both F1 and F2 differed significantly between baseline and all other phases ($p < 0.001$), except for F1 baseline and full perturbation (significant at $p < 0.012$). For S3, baseline and full perturbation F1 and F2 values were non-significantly different. F1 values were also non-significantly different between baseline and masking. S3's F2 values differed significantly between baseline and masking ($p < 0.001$) and both F1 and F2 values differed significantly between baseline and return ($p < 0.001$). For S4, baseline and full perturbation were non-significantly different for both F1 and F2, while baseline and all other phases were significantly different ($p < 0.001$). For S5, baseline and all other phases differed significantly for both F1 and F2 ($p < 0.001$). Under the assumption that sensorimotor compensation and adaptation are reflected in significant differences from baseline compared to full perturbation and masking (respectively), the implications of these statistical analyses are highlight in Table 3 (significant changes are indicated in red) which summarizes the change from baseline in F1 and F2 that occurred in the relevant conditions.

TABLE 3. Summary of F1 and F2 shifts (Hz) from baseline to full perturbation (compensation) and masking (adaptation). Significant shifts based on post-hoc comparisons are shown in red.

Participant	F1-Compensation	F2-Compensation	F1-Adaptation	F2-Adaptation
S1	68	-154	56	-157
S2	33	-128	56	-105
S3	39	-13	125	-341
S4	18	-45	56	-88
S5	98	-144	19	-90

DISCUSSION

The goal of this work was to evaluate the possibility of using a virtual vocal tract to elicit short-term sensorimotor learning (SA). Such an endeavor may prove useful in the development of novel forms of neurorehabilitation (Bastian, 2008), and could provide a novel landscape for studying the nature of feedback and feedforward mechanisms in speech motor control (Perkell, 2012). Based on an acoustic analysis of steady-state values for /e/, the current results indicate that three out of five typically-functioning participants demonstrated evidence of sensorimotor compensation and adaptation via a virtual vocal tract. To the extent that learning a novel articulator-acoustic mapping is a prerequisite to SA, the lack of consistency across participants in the current experiment could be evidence that some individuals are able to generate internal models for speech motor control with greater efficiency than others.

A second consideration that may have influenced participant learning is the somatosensory impact of the EMA sensors. To the extent that these sensors increase somatosensory awareness they may create a condition that strengthens somatosensory feedback and highlights established (speaker-specific) somatosensory goals (Nasir and Ostry, 2006, Tremblay et al., 2003). Such an increase in somatosensory awareness could reduce the capacity of some learners to establish a novel articulatory-acoustic mapping. Even if a novel mapping were established, increased somatosensory feedback could be implicated in increasing resistance to compensation and adaptation (Katseff et al., 2012).

Finally, the "voice" generated by the articulatory synthesizer deviates not only from the acoustic working space of a participant, but also from the quality of natural-sounding human speech. This unnatural quality could influence some participants' abilities to identify the acoustic consequences of their articulatory movements as speech. If a participant does not identify the acoustic output as being sufficiently "speech-like," he or she may not process speech-related acoustic information in a typical fashion, thus affecting the use of auditory feedback.

CONCLUSIONS

We completed sensorimotor adaptation experiments with five human participants who used a virtual vocal tract to learn a novel articulatory-acoustic mapping. Three of these participants produced acoustic modifications consistent with sensorimotor compensation and adaptation. These findings suggest that short-term speech learning through a virtual vocal tract is feasible. The long term goal of this work is to refine the current method and extend this research to allow for the study of sensorimotor learning in individuals with motor speech disorders. Improvements in our understanding of speech sensorimotor learning mechanisms in both normal and disordered talkers is critical to the development of novel approaches to neurorehabilitation.

ACKNOWLEDGMENTS

REFERENCES

Bastian, A. J. (**2008**). "Understanding sensorimotor adaptation and learning for rehabilitation," *Curr. Opin. Neurol.* 21 **6**, 628-633.

Berry, J. J. (**2011**). "Accuracy of the NDI Wave speech research system," *Journal of Speech, Language and Hearing Research* **54** 5, 1295.

Bultitude, J. H., Rafal, R. D. and Tinker, C. (2012). "Moving forward with prisms: Sensory-motor adaptation improves gait initiation in Parkinson's disease." *Frontiers in Neurology* **3**, 132.

Cai, S., Ghosh, S. S., Guenther, F. H. and Perkell, J. S. (**2010**). "Adaptive auditory feedback control of the production of formant trajectories in the Mandarin triphthong /iau/ and its pattern of generalization." *J. Acoust. Soc. Am.* **128** 4, 2033-2048.

Cai, S., Ghosh, S. S., Guenther, F. H. and Perkell, J. S. (**2011**). "Focal manipulations of formant trajectories reveal a role of auditory feedback in the online control of both within-syllable and between-syllable speech training." *The Journal of Neuroscience* **31** 45, 16483-16490.

Fant, G. (**1970**). *Acoustic Theory of Speech Production* (Mouton: The Hague).

Haith, A. M. and Krakauer, J. W. (**2012**). "Model-based and model-free mechanisms of human motor learning,". *Proc. Progress in Motor Control VIII.* In press.

Houde, J. F. and Jordan, M. I. (**2002**). "Sensorimotor Adaptation of Speech I: Compensation and Adaptation," *J. Speech Lang. Hear. Res.* **45** 2, 295-310.

Huckvale (**2009**). *VTDemo-Vocal Tract Acoustics Demonstrator* (Computer Program).

Katseff, S., Houde, J. and Johnson, K. (**2012**). "Partial Compensation for Altered Auditory Feedback: A Tradeoff with Somatosensory Feedback?" *Lang. Speech* **55** 2, 295-308.

Laver, K., George, S., Thomas, S., Deutsch, J. E. and Crotty, M. (**2012**). "Virtual reality for stroke rehabilitation (review)," *Eur. J. Phys. Rehabil. Med.* **9**.

Lehrer, N., Attygalle, S., Wolf, S. L. and Rikakis, T. (**2011**). "Exploring the bases for a mixed reality stroke rehabilitation system, part I: a unified approach for representing action, quantitative evaluation, and interactive feedback," *J. Neuroeng Rehabil.* **8**, 51.

Liu, X., Mosier, K. M., Mussa-Ivaldi, F. A., Casadio, M. and Scheidt, R. A. (**2011**). "Reorganization of finger coordination patterns during adaptation to rotation and scaling of a newly learned sensorimotor transformation," *J. Neurophysiol.* **105** 1, 454-473.

Maeda, S. (**1990**). *Compensatory articulation during speech: Evidence from the analysis and synthesis of vocal-tract shapes using an articulatory model* (Kluwer Academic Publishers, Boston, Massachussetts).

Maeda, S. (**1982**). "A digital simulation of the vocal-tract system," *Speech Commun.* **1** 3-4, 199-229.

Mazzoni, P. and Krakauer, J. W. (**2006**). "An implicit plan overrides an explicit strategy during visuomotor adaptation," The *Journal of neuroscience* **26** 14, 3642-3645.

Milenkovic, P. (2005). *TF32* (Computer Program). Madison, WI.

Mosier, K. M., Scheidt, R. A., Acosta, S. and Mussa-Ivaldi, F. A. (**2005**). "Remapping hand movements in a novel geometrical environment," *J. Neurophysiol.* **94** 6, 4362-4372.

Munhall, K. G., MacDonald, E. N., Byrne, S. K. and Johnsrude, I. (**2009**). "Talkers alter vowel production in response to real-time formant perturbation even when instructed not to compensate," *J. Acoust. Soc. Am.* 125 **1**, 384-390.

Mussa-Ivaldi, F. A., Casadio, M., Danziger, Z. C., Mosier, K. and Scheidt, R. A. (**2011**). "Sensory motor remapping of space in human-machine interfaces," *Prog. Brain Res.* **191**, 45.

Nagengast, A. J., Braun, D. A. and Wolpert, D. M. (**2009**). "Optimal control predicts human performance on objects with internal degrees of freedom," *PLoS computational biology* **5** 6, e1000419.

Nasir, S. M. and Ostry, D. J. (**2006**). "Somatosensory Precision in Speech Production," *Current Biology* **16** 19, 1918-1923.

Perkell, J. S. (**2012**). "Movement goals and feedback and feedforward control mechanisms in speech production," *Journal of Neurolinguistics* **25** 5, 382-407.

Pisella, L., Rode, G., Farne, A., Tilikete, C. and Rossetti, Y. (**2006**). "Prism adaptation in the rehabilitation of patients with visuo-spatial cognitive disorders," *Curr. Opin. Neurol.* **19** 6, 534-542.

Purcell, D. W. and Munhall, K. G. (**2006**). "Adaptive control of vowel formant frequency: Evidence from real-time formant manipulation," *J. Acoust. Soc. Am.* **120** 2, 966-977.

Purcell, D. W. and Munhall, K. G. (**2006**). "Compensation following real-time manipulation of formants in isolated vowels," *J. Acoust. Soc. Am.* 119 4, 2288-2297.

Reisman, D. S., Bastian, A. J. and Morton, S. M. (**2010**). "Neurophysiologic and rehabilitation insights from the split-belt and other locomotor adaptation paradigms," *Phys. Ther.* **90** 2, 187-195.

Reisman, D. S., Wityk, R., Silver, K. and Bastian, A. J. (**2007**). "Locomotor adaptation on a split-belt treadmill can improve walking symmetry post-stroke," *Brain* **130** 7, 1861.

Rossetti, Y., Rode, G., Pisella, L., Farne, A., Li, L., Boisson, D. and Perenin, M. T. (**1998**). "Prism adaptation to a rightward optical deviation rehabilitates left hemispatial neglect," *Nature* **395** 6698, 166-169.

Sternad, D., Abe, M. O., Hu, X. and Müller, H. (**2011**). "Neuromotor noise, error tolerance and velocity-dependent costs in skilled performance," *PLoS Computational Biology* **7** 9, e1002159.

Subramanian, S. K., Massie, C. L., Malcolm, M. P. and Levin, M. F. (**2010**). "Does provision of extrinsic feedback result in improved motor learning in the upper limb poststroke? A systematic review of the evidence," *Neurorehabil. Neural Repair* **24** 2, 113-124.

Tremblay, S., Douglas, M. S. and David, J. O. (**2003**). "Somatosensory basis of speech production," *Nature* **423** 6942, 866.

Villacorta, V. M., Perkell, J. S. and Guenther, F. H. (**2007**). "Sensorimotor adaptation to feedback perturbations of vowel acoustics and its relation to perception," *J. Acoust. Soc. Am.* 122 4, 2306-2319.