Auditory Motor Integration in Oral and Manual Effectors

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ABSTRACT. Sensorimotor integration of auditory feedback for oral and manual force control was compared in 10 healthy participants. Based on the notion that auditory-to-motor integration is a more typical form of feedback for oral articulators given their role in speech and singing, it was predicted that oral force generation would be more accurate and less variable on an auditory-motor task compared to manual force generation. However, finger force production showed similar accuracy and lower variability than lip force production. The authors propose that auditory feedback can be used for fine force control of both oral and manual effectors. Differences in performance are considered to arise from physiological differences between the effectors that are reflected in their typical functions. This novel study of oral and manual force control under auditory feedback is an important step in understanding how auditory information can be associated with fine force control.

Keywords: auditory feedback, force control, sensorimotor integration, variability

Fine control of volitional movements is fundamental to everyday life. The precision of volitional movement is based in part on the ability to utilize sensory information. This information is available through various modalities (e.g., visual, auditory, somatosensory, vestibular) and can provide a range of information encompassing how a motor act is being performed as well as if it has been completed satisfactorily. The majority of research has focused on the role of visuomotor processing in motor control, but clearly not all sensory outcomes for movements are visual. Certain highly functional types of movement, including speech and music, are specified in auditory terms (Guenther, Hampson, & Johnson, 1998). Although the visual goal of a manual movement differs from the auditory goal of an oral movement in biomechanical terms and neural pathways, successful completion of either task depends in part on intact sensorimotor integration.

In visuomotor studies comparing oral and manual force production, finger control has been found to be less variable and more accurate than lip, tongue, or jaw force control (Gentil & Tournier, 1998; van Steenberghhe, Bonte, Schols, Jacobs, & Schotte, 1991), even though highly precise oral force production under visual feedback has been documented (Andreatta, Barlow, & Finan, 1994). The finger also appears more suited in maintaining a stable kinematic position relative to the jaw with visual feedback, but the jaw is less variable and more accurate when only proprioceptive information is available (De Nil & Lafaille, 2002; Jacobs, van Steenberghhe, & Schotte, 1992). For these oral-manual motor comparisons, it has been proposed the jaw may be superior for proprioceptively guided tasks because visual feedback is not naturally available for oral movements so other sensory modalities must be used, whereas the visual information often available for manual movements is a typical or natural mode of sensory feedback.

In contrast, audition or auditory information is the primary and most effective sensory modality for learning and controlling oral effectors in speech and singing. As such, an advantage in force accuracy and variability may exist for oral effectors relative to manual effectors under auditory feedback. Important differences between speech movements and oral movements in general (Weismer, 2006; Ziegler, 2003), in that general oral movement control does not by necessity predict or determine speech production capabilities, but converting auditory information to vocal singing and speech gestures is a basic element of these motor skills. Oral motor control also does not naturally utilize visual feedback for fine control. Therefore, as a starting point for investigating the influence of audiomotor integration on force production, an advantage for oral effectors is proposed.

A series of studies by Sussman and colleagues established that oral and manual effectors can track changes in auditory signals for both isometric and kinematic tasks (Sussman, 1971; Sussman, MacNeilage, & Lumbley, 1974, 1975), but oral and manual performance were not compared in these studies. In the present study, oral and manual force control for discrete force pulses was compared. Target levels were varied to sample force control at a low-level force (15% maximal voluntary force [MVF]) and midrange force (30% MVF) as is commonly done in visuomotor studies (Sosnoff & Newell, 2006). This study is the first comparison of whether oral (lip) force control is more accurate and less variable than manual (index finger) force control under continuous auditory feedback.

Method

Participants

Ten individuals, ages of 20–30 years (4 women) provided informed consent to participate in the study. All participants were right-handed, had normal hearing in the speech frequencies (250–6,000 Hz) and did not have a history of neurological disorders, psychiatric disorders, speech-language disorders, or motor impairments. At the time of the study, none of the participants were taking medications for chronic

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disorders. None of the participants had more than 1 year of musical training and none had specific training for manual instruments such as the piano or guitar. The study was approved by the Institutional Review Board of the University of Illinois at Urbana-Champaign.

**Tasks**

The participants were instructed to produce a rapid force pulse with either the lower lip or right index finger (dominant hand) to match a target force and then return to baseline level. The force signal manipulated a voltage controlled oscillator (VCO) that converted the force signal into an acoustic pure tone. The frequency of the pure tone sinusoid increased linearly as force increased. The participant was instructed to match the force controlled variable tone (tracking tone) with a target tone (static frequency). The acoustic stimuli were presented dichotically via headphones (different signals in each ear) with the tracking tone always presented to the right ear while the target tone was always presented to the left ear. This configuration was associated with lower oral movement error in the auditory feedback studies reported by Sussman and colleagues (Sussman, 1971; Sussman et al., 1974, 1975).

MVF elicited by pushing on a transducer with the lip or finger was measured first for the articulators. Both the voltage and VCO frequency at MFV were recorded. Here, the term maximal voluntary force or MFV is used instead of maximal voluntary contraction or MVC to indicate that electromyography was not used to measure muscle contraction. The MFV for each participant determined the frequency range controlled by the VCO (Tucker Davis Technologies-RP2.1, Alachua, FL). The target force levels were then set at 15% and 30% of MFV. The voltage of the baseline or resting force level was adjusted to generate a frequency of 400 Hz with the transducer in place. The consistent amplifier gain settings used for all participants determined that target frequencies ranged from 475–500 Hz for the 15% target and 550–600 Hz for the 30% target. A 15-s rest period was provided between each trial.

The tracking tone was played continuously while the target tone was presented for 3 s. As soon as the target tone was heard, the participant attempted to match the target tone as rapidly and accurately as possible by increasing the force exerted on the transducer. After reaching target level, the participant was instructed to relax and return to baseline. Because voltage was linearly related to frequency, the participants could continuously compare frequency differences between the tracking and target tones. Participants repeated this task 15 times. The order of the finger and lip was counterbalanced across participants.

Close to target level, the differences in frequency between the acoustic signals elicit a beating sensation in both ears. This phenomenon called binaural beats is heard when two tones that are close in frequency are presented dichotically (to both ears) between the range of 300–900 Hz (Moore, 2004). When the frequencies match, the participant perceives a single tone at target frequency via binaural fusion (Hamill & Price, 2008). During training, the experimenter confirmed that participants could both hear the beats and pure tone blending and understood that matching or fusing the tones indicated accurate performance.

The participants reported they had not participated in an oral motor control study before, but they adapted quickly to the setup. Each participant could perform the auditory matching tasks after instructions were provided and each individual showed good performance during two learning trials when a continuous target tone was presented. Each participant completed the study and overall, fewer than 10 trials across the participants were excluded from the analysis due to excessive variation or late starts. In those cases, participants reported their attention had drifted or they started the trial more than 3 s after trial onset.

**Instrumentation**

Lower lip force was recorded using a strain-gauge transducer mounted on a rigid cantilever beam (Barlow & Abbs, 1983). The device built by Neuro Logic, LLC (Lawrence, KS) has been used frequently in oral force production studies (Barlow & Burton, 1990; Gentil & Tournier, 1998). The transducer shown in Figure 1A has two arms forming a bite bar. Each arm of the bite bar was first coated with dental putty used for denture molds. Then the participant bit down on the dental putty forming a mold that held the transducer in place. The transducer was positioned so that the participant’s lower lip fit into a small saddle (Figure 1A). Producing a closing force by the lower lip against the saddle put strain on the cantilever beam generating the voltage that controlled the digital VCO. To minimize head and jaw movements, the participants rested their jaw within a chinrest that also allowed placement of the forehead against a bar (see setup in Figure 1B). The oral transducer is sensitive to a force of less than 0.1 N and is linear over the 0.1–20.0 N range. The mold and transducer were easily removed without residue or discomfort at the end of the experiment.

Index finger force was acquired using an Eltran load cell (Eltran EL-FS-B3–50 N load cell, diameter 1.27 cm; MSI Sensors, Hampton, VA), which is a small cylinder mounted in a stainless-steel frame displayed in Figure 1C. Participants compressed the load cell by abducting their right index finger (always using the dominant hand) while resting their right hand comfortably in a prone position. The load cell showed the same sensitivity and linearity as the oral transducer. Participants did not report fatigue or discomfort following the study.

The voltage signals from each transducer were amplified (Bio-Communication Electronics, Madison, WI), low-pass filtered at 50 Hz and then digitized (1000 samples/s) using a Tucker-Davis Technologies RP2.1. The RP2.1 converted the force signal voltage into a frequency with a baseline of 400 Hz that was linearly related to the force voltage (voltage controlled oscillator). The RP2.1 also generated the target
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FIGURE 1. The oral transducer and experimental setup is shown for each effector. (A) The lower lip transducer has two extensions that form the bite bar (1). The participant places the lower lip against the small saddle (2). (B) The setup for the oral effector is shown with a participant resting his jaw on a chinrest and forehead on a frame to minimize jaw and head movements, respectively. (C) The setup for the manual effector is shown with the arm in a comfortable prone position and the index finger in a frame resting on the load cell.

signals and simultaneously recorded the voltage and acoustic signals. Both transducers are highly stable and linear with respect to the force applied and output of the VCO.

Dependent Variables

The dependent variables included measures of accuracy and variability that were determined separately for each effector and force level. Accuracy on each trial was measured by determining the constant error of the peak of the force pulse (Schmidt & Lee, 1999). Variability was measured by calculating variable error and the coefficient of variation (CV) of the peak force (Schmidt & Lee). The peak rate of change was estimated by taking the first derivative of the force pulse and finding the average of the 15 trials. The standard deviation and CV of peak force rate were also determined.

A two-way repeated measures analysis of variance (ANOVA) was used to compare lower lip versus index finger performance (effector condition) at 15% and 30% MVF (target condition). This 2 × 2 factorial design was employed separately for each dependent variable. The probability of a Type I error was set at \( p < .05 \) for all comparisons.

Results

Mean of Peak Force

In general, the mean (peak) force values approximately doubled in the 30% condition relative to the 15% condition (target main effect; \( F(1, 9) = 30.2, p < .05 \), as illustrated in Figure 2. An interaction between the target and effector conditions was detected (\( F(1, 9) = 8.17, p < .05 \)), which resulted from a higher peak lip force for the 15% target compared to the finger and no difference between effectors for the 30% target.

Constant Error

Constant error was negative for all effectors and force levels, except for a positive lip force at the 15% force level (see Figure 3). This indicated that participants tended to undershoot the auditory target except for lip overshoot at the lower force level. There was an effect of target level as constant error became more negative for the 30% target level (target main effect; \( F(1, 9) = 23.4, p < .05 \)) that is greater undershoot. The target by effector interaction was not significant but the 15% target is of considerable interest because 8 of 10 participants had positive constant error (overshoot) for the lip compared to only 2 of 10 participants for the finger.

Variable Error

The lower lip was more variable than the finger as shown by higher variable error at each target level (effector main effect; \( F(1, 9) = 10.2, p < .05 \)). Variable error appeared to
scale with target level but this effect did not reach significance (Figure 4).

**Coefficient of Variation**

Consistent with the findings for variable error, the lip showed significantly higher CV than the finger (effector main effect; \( F(1, 9) = 5.7, p < .05 \)), as illustrated in Figure 5. The CV of the lip remained similar across force levels but the CV of the finger decreased for the 30% target relative to the 15% target.

**Discussion**

This study is the first comparison of continuous auditory feedback for oral versus manual force control. Our main findings are that the accuracy of lower lip forces and manual forces are similar across force levels with both showing a decrease in accuracy at the higher force level. Variability was lower for manual force production than lower lip force production. These results extend previous comparisons of oral and manual force control under visual feedback (Gentil & Tournier, 1998).
Accuracy and Variability of Force Production

The high accuracy of both effectors for the lower force target was interestingly differentiated by the systematic trends for target undershot by the finger (negative CE) and overshoot for the lip (positive CE). Similar overshoot was reported for lower lip force pulses by Barlow and Burton (1990) using similar force levels, but the feedback modality was visual. Lip force overshoot for both auditory and visual targets (Barlow & Burton) suggests the pattern may be independent of feedback modality. However, this effect may depend on the force target level because both effectors showed undershoot for the higher force level.

The lip overshoot at the lower target level was associated with higher peak force rates than the finger, which provides some explanatory information for the overshoot. It does not account, however, for the similar oral-manual accuracy at the higher force level, even though lip force rate was significantly higher for both levels. As discussed subsequently in more detail (see Effector Differences), lower lip motor units and muscle fibers may be more adapted to producing rapid force pulses for speech sounds, but do not function as accurately as the finger for invariant kinetic targets.

Variability analyses aid in determining whether control strategies under auditory feedback are generally more effective for an effector or a given force level. Across the measures of variability used in this study (i.e., variable error and CV), finger force variability was lower. Even though participants were able to perform the task with the lip, lip force control remained less consistent, but the difference between effectors was similar across target levels.

When the effect of the mean force was controlled by determining the relative variability (CV), it was confirmed that lip variation under auditory feedback was not modulated by force level. In contrast, the CV of finger force decreased with force level. Somewhat surprisingly therefore, neuromuscular control of manual force appears to be more flexible under auditory feedback than oral force based on lower variability and similar accuracy. We do point out, however, that the CV of the lip was not necessarily poor, it was just higher than finger CV. We believe auditory feedback can be effective in modulating lip motor control, but lip control may have inherently higher variability than finger force at the force levels tested in this study. Lip muscle forces can clearly be trained to produce fine auditory targets for musical instruments and speech sounds, but this training would involve considerable motor learning. Also, highly accurate lip force contractions with low variability have been documented under visual feedback at levels similar to that of the 15% force levels used in the present study (Andreatta et al., 1994; Barlow & Burton, 1990).

Effector Differences

Certain effector differences need to be considered in comparisons of oral-manual motor control. First, the muscles of facial expression that influence mouth aperture and shape, including lower lip elevation, lack muscle spindles (Stal,
Ericksson, Ericksson, & Thornell, 1987, 1990), whereas the finger flexion muscles predominantly used for this task have dense spindle populations (Stal et al., 1987). Secondly, unlike the finger flexion musculature, lip muscles do not act around a joint and instead originate from either bone or soft tissue and then insert into soft connective tissue. Third, labial muscle contraction only needs to be sufficient to shape the oral opening for an intended acoustic target or seal the mouth during chewing. These activities do not require maintenance of fixed postures, generation of high force levels, or necessarily fine accuracy (as long as the auditory target is reached), but rather flexibility and speed, which is perhaps consistent with the higher lip force rates and overshoot observed in this study and by others (Gentil & Tournier, 1998). Given these flexibility and stretching requirements for rapid speech, singing, or chewing, labial motion could instead be hindered by muscle spindles or attachments to joints. The finger flexion musculature is more often used to hold consistent postures and stable contractile force levels over long periods. A final point is that differences in the muscle fiber typology of the muscles may contribute to effector differences. Lip muscles apparently have a large representation of Type II fast-twitch fibers (Stal, 1994; Stal et al., 1990) whereas the finger muscle has a larger population of Type I slow-twitch fibers (Stal et al., 1987). The fast-twitch fibers of lip muscles could dispose these muscles to rapid contractions for short duration activities. Finger forces, on the other hand, may be better suited to prolonged force tasks based on the presence of muscle and tendon receptors as well as the muscle-fiber composition. These different characteristics may partially account for the effector differences reported in the present study, especially because a similar pattern of oral-manual differences in force production was reported by Gentil and Tournier (1998). Yet, important questions concern the magnitude of differences between effectors, force levels, feedback characteristics, and the type of task.

**Influence of Auditory Feedback on Force Production**

This auditory-force feedback study offers a novel approach to studying sensorimotor control of fine force production in different effectors. A principal role of auditory-to-motor (or audiomotor) integration is to support speech motor learning in children. Early in the speech acquisition period, auditory information is used as online feedback to shape ongoing production to approximate the auditory patterns of the child’s language environment (Callan, Kent, Guenther, & Vorperian, 2000). As children learn their language, they gradually rely less on online feedback (Guenther, 1995), but there is always some dependency on auditory feedback for error correction. Otherwise, online auditory information remains important throughout life for monitoring pitch and loudness, vocal training, or learning a second language (Bauer, Mittal, Larson, & Hain, 2006; Burnett, Freedland, Larson, & Hain, 1998; Lane et al., 2007; Villacorta, Perkell, & Guenther, 2007).

We consider that our present results reflect a relatively early stage in associating auditory feedback with motor commands, somewhat similar to musical tasks in which a motor strategy is implemented to reach and hold a target note. When a person first learns to produce a note of an instrument, consistent online feedback is needed to evaluate if the note was produced correctly. As learning proceeds the individual acquires motor commands that consistently produce the note and become less dependent on the sensory feedback. The task used in the present study is amenable to testing within a motor learning paradigm. We expect that learning patterns would be observed for both the finger and lip, but based on the present findings, the rate of learning would be faster for the finger.

Auditory-motor integration was potentially influenced in the present study by the presence of binaural beats. Binaural beats are heard when two tones that are close in frequency are presented dichotically (to both ears) between the range of 300–900 Hz (Moore, 2004). At frequencies in which the target and tracking tone match exactly, the two tones perceptually fuse and a single tone without beating is perceived. Each participant understood the goal of the task was to achieve the fusion of the tones. However, the presence of beats may have biased participants to be less accurate than their actual capability because the beating indicated a close proximity to the target frequency. On the other hand, oscillation of the tracking signal within the range of beat frequencies suggests participants were approaching an auditory target and achieving a generally controlled variation around the target. In subsequent work, the criterion for accuracy could be maintaining force level within the region of binaural beat perception. One strategy to avoid the beat phenomena is to use frequencies higher than range of binaural beats (> 1500 Hz).

The present study bears some similarity to a series of auditory-to-motor integration studies conducted during the 1970s that required participants to match a target signal by moving an effector that controlled a VCO (either finger, jaw, or tongue; Sussman, 1971; Sussman et al., 1974, 1975). These movement conditions only required low isotonic force levels and oral-manual performance was not contrasted directly. Only one study in the series used isometric force level monitored by EMG to control a tracking signal, but a force transducer was not used. The purpose of these studies differed from the present study because the authors were investigating auditory laterality differences. The studies essentially compared whether presenting the dynamic auditory signal to the right ear led to higher accuracy than if it was presented to the left ear. In general, the predicted right ear advantage was found but it was only tested for continuous tasks (not for dynamic tasks). These studies generally confirmed that auditory-to-motor integration for tracking was possible, but results from the kinematic conditions of these studies cannot be compared directly to the present findings. We did follow the major finding of the studies by presenting the dynamic stimulus to the right ear of our participants (all right-handed) with the intention of facilitating better performance.
The only study identified that used continuous auditory feedback generated by a VCO for force control contrasted visual versus auditory feedback (Prodoehl, Yu, Wasson, Corcos, & Vaillancourt, 2008). Oral and manual effectors were not compared so the results cannot be directly related to our findings, but the experimental paradigm established the feasibility of such studies. Static force targets were not used in the study; instead, participants increased finger adduction force to match a dynamic force target signal that increased in frequency with a ramp shape (Prodoehl et al.). The visual feedback condition was similar in that participants had to match a steadily increasing force target level by increasing finger adduction. Force control was similar in both the auditory and visual conditions, which was not explained, but the paradigm is of interest for testing whether oral force production shows improved performance for dynamic targets.

Conclusion

Auditory-motor integration with continuous feedback allowed for the production of stable continuous force contractions at 15% and 30% MVF for both lower lip and index finger flexion with index finger flexion being less variable. The pairing of continuous auditory feedback with the force task resembles the production and possibly early learning of musical notes. The present study is one approach to understanding how auditory feedback can influence fine motor control. Further research is needed to compare the contribution of visual and auditory information to oral and manual force production.

REFERENCES


