Prior short-term habituation to auditory feedback delays does not mitigate their disruptive effect on speech auditory-motor adaptation

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ABSTRACT

Perceiving the sensory consequences of our own actions with a delay alters the interpretation of these afferent signals and impacts motor learning. For reaching movements, delayed visual feedback of hand position reduces the rate and extent of visuo-motor adaptation, but substantial adaptation still occurs. Moreover, the detrimental effect of visual feedback delay on reach motor learning—in particular its explicit component—can be mitigated by prior habituation to the delay. Auditory-motor learning for speech has been reported to be more sensitive to feedback delay, and it remains unknown whether prior habituation to auditory delay reduces its negative impact on learning. We investigated whether 30 minutes of exposure to auditory feedback delay during speaking (a) affects the subjective perception of this delay, and (b) mitigates its disruptive effect on speech auditory-motor learning. During a speech adaptation task with real-time perturbation of vowel spectral properties, participants heard this frequency-shifted auditory feedback with either no delay, 75 ms delay, or 115 ms delay. In the delay groups, half of the participants had been exposed to the delay throughout a preceding 30-minute block of speaking whereas the remaining participants completed this initial block without delay. Even though habituation reduced the subjective perception of delay, no improvement in adaptation to the spectral perturbation was observed as compared with non-habituated participants. Thus, short-term habituation to auditory feedback delays is not effective in reducing the negative impact of delay on speech auditory-motor adaptation, suggesting the involvement of predominantly implicit learning mechanisms in this form of sensorimotor learning.

NEW AND NOTEWORTHY

Speech auditory-motor adaptation in response to a spectral perturbation was substantially reduced when feedback was delayed by 75 or 115 ms. Thirty minutes of prior exposure to the same delay while speaking without spectral perturbation was effective in reducing participants' subjective perception of the delay. However, such prior habituation was ineffective in remediating the detrimental effect of feedback delay on speech auditory-motor adaptation. Results suggests that speech sensorimotor learning is dominated by implicit learning mechanisms.

1. Introduction

An important consequence of delays in neural transmission and processing is that sensory information resulting from self-generated movements is not received by the brain in real-time. This can be problematic for the online use of sensory feedback in the planning and control of motor behaviors, including the integration of multiple sources of sensory input (each with a potentially different delay). When one or more of the sensory signals (e.g., vision) is also subject to additional, environmentally induced delays, motor control for tasks such as hand-writing can be severely disrupted (Morikiyo and Matsushima 1990; Smith et al. 1960; Tamada 1995). Furthermore, it has been shown that perceiving the sensory consequences of one's actions with a delay as short as 100 ms can alter the interpretation of afferent signals, typically causing them to be attributed to an external source rather than a self-generated action (Blakemore et al. 2000).

The effects of feedback delay have also been explored in the context of sensorimotor *learning* given that the latter requires the correct updating of internal representations of the association between motor commands and their sensory consequences in a particular environment. For example, studies have experimentally manipulated the visual feedback delay during reaching tasks in which participants wore prism glasses (Kitazawa et al. 1995; Tanaka et al. 2011) or in which the location of a computer cursor representing hand position was rotated around the center of the workspace (Honda et al. 2012a). Visual feedback representing only the final hand position at movement completion (Kitazawa et al. 1995; Tanaka et al. 2011) or the entire motion of the cursor (Honda et al. 2012a) was shown either with no delay (other than that inherent in the instrumentation setup, which by itself was sometimes as long as 60 ms) or after experimentally induced additional delays ranging from 50 to 10000 ms. Such visual feedback delays were found to negatively impact the initial rate of adaptation (i.e., the slope of a learning function), but all studies reported that a robust degree of visuo-motor adaptation did occur by the end of training. With a delay of 100 ms, the final extent of prism adaptation was essentially unaffected in Tanaka et al. (2011) and reduced by approximately 35-40% in Kitazawa et al. (1995). With a delay of 200 ms, visuo-motor rotation learning was reduced by approximately 20% in Honda et al. (2012a). Even with a much longer delay of 5000 ms, prism adaptation was not eliminated but reduced by approximately 50% in Kitazawa et al. (1995). Thus, while delaying visual feedback of hand position often had a statistically significant impact on the rate and extent of visuo-motor adaptation[1], the disruptive effect on the extent of learning has been limited, and substantial motor learning still occurs under those circumstances.

Interestingly, the potentially disruptive effects of delays in motor-related sensory signals may be reduced in part by neural mechanisms that can predict and compensate for such effects (Miall et al. 1993; Miall and Jackson 2006). Numerous studies have shown that sensory predictions related to self-generated movement take account of the temporal relationship between the motor and sensory processes and are modified through experience. Following prolonged exposure to a consistent time delay between an action such as a button press and a sensory consequence such as a tone, subjects begin to perceive the sensory event as shifted in time toward the action (Haggard et al. 2002; Haggard and Clark 2003; Park et al. 2003; Stetson et al. 2006; Heron et al. 2009). Similar perceived changes in the relative timing of sensorimotor signals have been observed in tasks involving visual or tactile feedback (Park et al. 2003; Stetson et al. 2006; Heron et al. 2009). Recently, it has been demonstrated that the attenuation of the perception of self-touch (as compared with external stimulation) also rapidly becomes delayed

[1] It has been shown that visual feedback delays of 75 or 150 ms during reaching movements had no statistically significant effect on adaptation to a force field (i.e., a somatosensory perturbation), but in that case even the complete absence of visual feedback did not significantly disrupt learning (McKenna et al., 2017).

when participants consistently experience a delay between their movement and the perceived touch (Kilteni et al. 2019).

Most important for the present work, a small number of studies have examined whether such plasticity in the perception of the temporal relationship between motor actions and their sensory consequences can be leveraged for motor *learning*. In other words, can experience-based plasticity in the temporal aspect of sensory predictions negate the otherwise detrimental effects of feedback delays on motor learning? Initially, this appeared to be not the case as Tanaka et al. (2011) found no improvement in prism glass adaptation with 136 ms visual feedback delay (100 ms added delay, 36 ms equipment delay) if subjects had also experienced the same delay before vision was shifted. However, in this Tanaka et al. (2011) study of pointing movements, (a) prior delay exposure was limited as it occurred only during the 60 baseline trials before the visual shift was implemented, (b) the subjectively perceived delay after this short period of exposure was still 96 ms, (c) the visual perturbation was introduced abruptly (thus, leading to subject awareness and explicit learning involving the use of cognitive strategies), and (d) the task was completed with only movement endpoint feedback rather than full trajectory feedback. In contrast, in studies of reaching movements completed with a 20-degree visual feedback rotation that was introduced gradually and with full motion path feedback, Honda (2012a, 2012b) tested whether the negative impact of a 260 ms visual feedback delay (200 ms added delay, 60 ms equipment delay) could be reduced by first habituating subjects to the delay for 100 or 120 movements, depending on the study. Findings revealed that subjects who experienced this amount of prior exposure to the delayed feedback showed improved learning in the subsequent adaptation task as compared with subjects without prior exposure to feedback delay. Thus, studies of sensorimotor adaptation in visually-guided arm movements indicate not only that delayed sensory feedback during a motor task results in consistent but limited effects on motor learning, but also that prior habituation to the feedback delay can mitigate these disruptive effects on visuo-motor learning.

In contrast with visuo-motor learning in the upper limb, the sensorimotor control of *speech articulation* appears to be much more sensitive to feedback delays. Max and Maffett (2015) examined adaptation in subjects' vowel production when the feedback signal was manipulated such that the frequencies of all resonance peaks (i.e., formants) were shifted upward, and this feedback signal was also delayed by 0, 100, 250, or 500 ms (in addition to a 10 ms delay inherent in the equipment). In the 0 ms delay condition, a robust adaptation effect was observed over 120 trials with altered auditory feedback. With all delays of 100 ms or more, however, adaptation was completely absent. In a later study, Mitsuya et al. (2017) also observed a nearly complete elimination (~90% reduction) of speech adaptation to altered feedback involving a shift of only the first formant when this signal was delayed by 100 ms. Hence, as compared with visual feedback for upper limb movements, the processing of auditory feedback for the adaptive learning of oral speech movements may depend much more strongly on a very tight temporal coupling between motor events and their sensory consequences.

It is plausible, but as of yet unconfirmed, that this much stronger effect of delayed feedback on sensorimotor learning for speech may relate to a fundamental difference in the underlying learning mechanisms. For example, evidence to date indicates that speech auditory-motor adaptation represents an almost entirely implicit form of learning. First, unlike standard visuo-motor tasks, naive subjects are completely unaware of which vocal tract movement strategies can compensate for the implemented formant-shift perturbation (e.g., for a simultaneous upward perturbation of the first two formants F1 and F2, oral opening should be reduced to compensate in F1 and tongue protrusion should be reduced to compensate in F2 or smaller compensatory changes in both formants could be achieved through lip protrusion or rounding). Second, even when speech auditory-motor adaptation occurs in response to an abruptly introduced perturbation, subjects' trial-by-trial reports indicate that they are unaware of having made any changes in their speech output (Kim and Max 2020). Third, there is no difference in the amount of speech adaptation to pitch-shifted auditory feedback in conditions where participants are instructed to either compensate or ignore the feedback (Keough et al. 2013) or in speech adaptation to formant-shifted auditory feedback conditions where participants are instructed to compensate, to ignore the feedback, or to explicitly avoid compensating (Munhall et al. 2003). Consequently, task differences in the involvement of implicit vs. explicit learning mechanisms may play a role in the differential effects of sensory delays on speech and limb adaptation. This suggestion is consistent with recent work showing that, in upper limb motor learning, feedback delays negatively affect implicit learning but not explicit strategy selection (Brudner et al. 2016; McDougle and Taylor 2019; Schween and Hegele 2017). It follows, then, that feedback delays may have only a relatively minor impact on visuo-motor reach adaptation because it is characterized by a small implicit component and a large explicit component, at least in the case of an abruptly introduced perturbation (Anguera et al. 2010; Fernandez-Ruiz et al. 2011; McDougle et al. 2016; Taylor et al. 2014) or a gradually introduced perturbation with reward feedback (Holland et al. 2018). In contrast, the detrimental impact of feedback delays on auditory-motor speech learning may result from this type of learning being largely or exclusively implicit in nature (Keough et al. 2013; Kim and Max 2020; Munhall et al. 2003).

If it is true that speech auditory-motor adaptation is entirely dependent on implicit learning mechanisms, then even prior habituation to auditory feedback delays may fail to reduce the known disruptive impact of such delays on this form of adaptation (again in contrast with visually-guided arm movements where prior habituation is helpful; see review above). Here, we directly investigate the presence vs. absence of such a habituation-based facilitatory effect by asking whether pre-exposure to a delay in speech auditory feedback will (a) alter participants' subjective perception of the imposed delay prior to and during completion of a speech auditory-motor adaptation task, and (b) mitigate the previously documented disruptive effects of such a delay on the extent of speech auditory-motor adaptation.

2. Methods

2.1 Overall design

Fifty-five adults with no reported history of speech, hearing, or neurological disorders participated after providing written informed consent (all procedures were approved by the Institutional Review Board at the University of Washington). Each participant was pseudo-randomly assigned to one of five groups so that each group included 5 men and 6 women (age information per group provided below). Fifty-four participants passed a pure tone hearing screening at 20 dB HL for the octave frequencies from 250 Hz to 4 kHz (tested in both ears separately). The remaining participant had a threshold of 25 dB HL at 250 Hz for the left ear, but passed at 20 dB HL in both ears for all other frequencies.

The study involved a *Delay Exposure* task (blocks of word reading and picture naming completed with or without feedback delay depending on group assignment) followed by an *Auditory-Motor Adaptation* task (blocks of word reading with formant-shifted auditory feedback completed with or without feedback delay depending on group assignment). Thus, the five groups differed in the amount of delay to which they were exposed in the adaptation task and whether or not they first habituated to this delay in the exposure task (Figure 1A):

(1) no delay in the exposure task, no delay in the adaptation task (*Control Group*; age *M* = 24.09 years, *SD* = 5.70, range = 18-35)

(2) no delay in the exposure task, 75 ms delay in the adaptation task (*Short-Delay No-Habituation Group*; age *M* = 22.64 years, *SD* = 5.90, range = 18-39)

(3) 75 ms delay in the exposure task, 75 ms delay in the adaptation task (*Short-Delay Habituation Group*; age *M* = 24.82 years, *SD* = 6.40, range = 18-42)

(4) no delay in the exposure task, 115 ms delay in the adaptation task (*Long-Delay No-Habituation Group*; age *M* = 23.27 years, *SD* = 6.10, range = 18-34)

(5) 115 ms delay in the exposure task, 115 ms delay in the adaptation task (*Long-Delay Habituation Group*; age *M* = 24.18 years, *SD* = 4.47, range = 19-32)

2.2 Delay Exposure task

In the *Delay Exposure* task, subjects produced consonant-vowel-consonant (CVC) words for 30 minutes while hearing their auditory feedback with either a minimal 10 ms delay intrinsic to the involved equipment (labeled "no delay" in the current study; used for the *Control Group* and the two *No-Habitation Groups*), a total delay of 75 ms (10 ms equipment delay plus 65 ms added delay; used for the *Short-Delay Habituation Group*), or a total delay of 115 ms (10 ms equipment delay plus 105 ms added delay; used for the *Long-Delay Habituation Group*). The task was divided into six 5-minute blocks, with blocks alternating between word reading and picture naming (60 trials per block; Figure 1B) to reduce monotony during this relatively long task. For each block, orthographically presented words were drawn randomly from a set of 180 different items or pictorially presented words were drawn randomly from a set of 72 different images.

Subjects' acoustic speech output was captured with a microphone (SM 58, Shure) positioned 15 cm from the mouth, amplified (DPS II, Applied Research and Technology), routed through a digital vocal processor capable of implementing delays (VoiceOne, TC Helicon, controlled through Musical Instrument Digital Interface [MIDI] signals from a computer workstation), and played back to the subject through insert earphones (ER-3A, Etymotic Research). Immediately prior to each recording session, the intensity of this speech feedback system was calibrated using a 2 cc coupler (Type 4946, Bruel & Kjaer) connected to a sound level meter (Type 2250A Hand Held Analyzer with Type 4947 ½" Pressure Field Microphone, Bruel & Kjaer). During this calibration process, amplification levels were adjusted such that a speaking intensity of 75 dB SPL at the microphone also resulted in an acoustic feedback signal of 75 dB SPL in the insert earphones.

After each block of 60 trials, subjects reported their subjective perception of any delay in the auditory feedback by marking, with a computer mouse, a location along a visual-analog scale presented on a laptop computer monitor (Figure 1B). The scale was presented by means of the Adaptive Visual Analog Scales (AVAS) software program (Marsh-Richard et al., 2009). It was presented as a horizontal 75 mm line across the middle of the screen, with the left and right anchors labeled "No delay" and "Longest delay," respectively. Mouse clicks along the visual line were automatically recorded by the AVAS software as a numerical score ranging from 0 (extreme left end of the scale) to 100 (extreme right end of the scale). Prior to testing, participants were first thoroughly familiarized with the scale by completing a training procedure

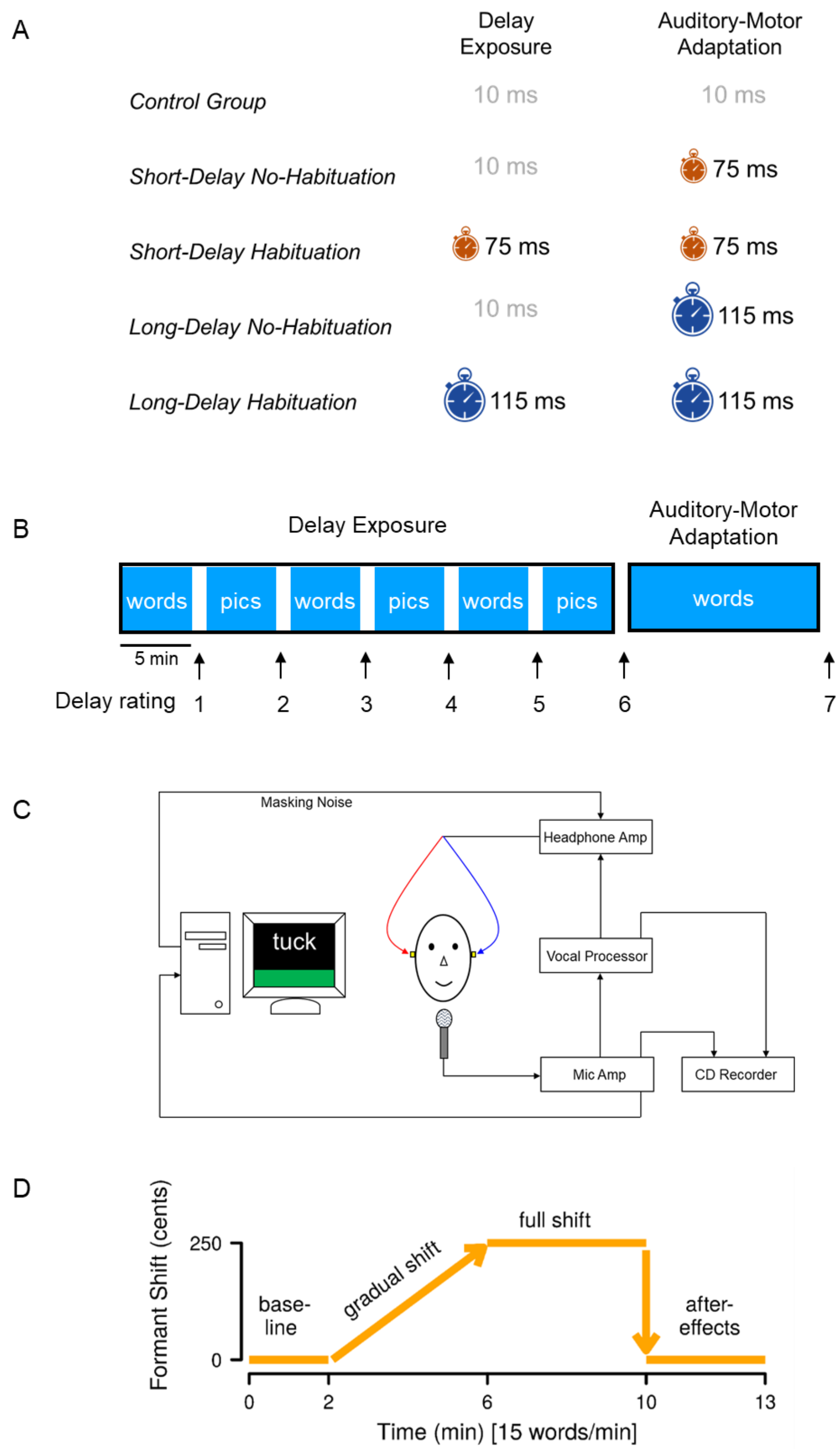

Figure 1. *(A) Auditory feedback delay experienced by each of five subject groups during the Delay Exposure task and the subsequent Auditory-Motor Adaptation task. (B) Sequence of speech tasks completed in the Delay Exposure task (alternating blocks of word reading and picture naming while exposed to delayed or non-delayed auditory feedback depending on group assignment) and the Auditory-Motor Adaptation task (production of target words while exposed to formant-shifted auditory feedback that was delayed or non-delayed depending on group*

assignment). Subjects rated perceived auditory delay following each speech production block. (C) Instrumentation setup for both the Delay Exposure task and the Auditory-Motor Adaptation task (with masking noise used only in the Adaptation task). (D) Time course of the formant-shift feedback perturbation during the Auditory-Motor Adaptation task.

using the AVAS software. Subsequently, they were familiarized with the "No delay" and "Longest delay" anchors of the scale and a point exactly in the middle of the scale. This was accomplished by letting subjects produce 10 CVC words in each of the following three auditory feedback conditions: only the 10 ms hardware-intrinsic delay, a total delay of 150 ms, and a total delay of 75 ms. Thus, the short-delay habituation condition of the actual experiment corresponded to the middle of the scale, and the scale extended well beyond the value corresponding to the long-delay habituation condition of the actual experiment in order to minimize ceiling effects.

Instructions to all subjects during the familiarization phase were as follows: No delay – "What you will hear now is the best that our equipment can do, so you will hear your own speech with no delay," and after completion of 10 productions "If you hear yourself this way, with no delay in the signal, you should click all the way to the left on the scale where it says no delay"; 150 ms delay – "What you will hear now is the longest delay that could ever happen in our equipment," and after 10 productions "If you hear yourself with a delay as long as what you just heard, you should click all the way to the right on the scale where it says maximum delay"; 75 ms delay – "What you will hear now will be a delay that is right in the middle between the best and worst possible situations that you just heard," and after completion of the productions "Could you tell that the delay was in the middle between the best and the worst possible? If you think that the delay that you hear is halfway between the best and worst possible you should click in the middle of the scale"). In this familiarization phase, the middle delay of 75 ms was always presented last, but the order of no delay and the longest delay of 150 ms was varied across subjects.

2.3 Auditory-Motor Adaptation task

The *Auditory-Motor Adaptation* task (Figure 1C) assessed subjects' speech adjustments to a frequency perturbation in the auditory feedback when this feedback signal was heard with a delay that—depending on group assignment—subjects had or had not been exposed to during the *Delay Exposure* task. The task involved producing 65 epochs of the three monosyllabic words "tech," "tuck," and "talk" for a total of 195 productions. The three words were randomized within each epoch and individually presented in the top half of a computer screen in front of the subject. Subjects' speech was transduced, routed, and played back in the same manner as described above for the *Delay Exposure* task, but pink masking noise was also mixed into the earphones at 68 dB SPL to minimize the availability of non-manipulated bone-conducted feedback prior to onset of the delayed earphones signal (see Max & Maffett 2015 for more details on the required masking level). Subjects were aided in maintaining a consistent speaking level by presenting color-coded visual feedback about speech intensity in the bottom half of the computer screen, with a target level between 72 and 78 dB SPL as measured at the microphone (15 cm from the mouth).

The frequency perturbation in the adaptation task consisted of an increase in the frequency of all formants (i.e., vowel resonances) to a maximum shift of +2.5 semitones, a manipulation that has been shown consistently to induce speech auditory-motor adaptation if implemented in real-time without delay (Daliri & Max, 2018; Max & Maffett, 2015; Max, Wallace, & Vincent, 2003). The formant shift implementation followed the same time course for all participants (Figure 1D): 30 trials with unaltered feedback (*baseline* phase); 60 trials during which the formant frequencies were incrementally increased to a maximum shift of +2.5 semitones (*ramp shift* phase); 60 trials during with the feedback shift was maintained at +2.5 semitones (*full shift* phase); and 45 trials after unaltered feedback had been restored (*after effects* phase or washout phase). Depending on specific group assignment, this formant-shifted auditory feedback signal was presented into the subject's earphones with one of the delays used during the *Delay Exposure* task: no delay (other than the 10 ms equipment delay), a total delay of 75 ms, or a total delay of 115 ms. After completion of the *Auditory-Motor Adaptation* task, all subjects provided one final rating of their subjective perception of feedback delay using the visual analog scale described above.

2.4 Data processing and analysis

Subjects' speech was digitized directly onto a computer (16-bit, 44.1 kHz) and then analyzed offline using custom software that combines routines from Praat (Version 6.0.39; Boersma et al., 2018) and Matlab (The Mathworks, Natick, MA). Specifically, we extracted the first and second formant frequencies (F1 and F2), averaged over the middle 20% of each trial's vowel portion, by means of Praat's default linear predictive coding algorithm (Boersma et al., 2018). In rare cases of speaking errors or formant tracking difficulties, the F1 and F2 values for missing trials were replaced by estimates linearly interpolated from neighboring productions of the same word.

The extracted F1 and F2 frequencies in Hertz (Hz) were then normalized within each speaker by transforming each trial to *cents* units (100 cents = 1 semitone) using the following formula:

$$F_{cents} = 1200 \, Log_2 \, (F_{Hz} / B_{Hz})$$

where F_{Hz} corresponds to the trial's formant frequency in Hz, and B_{Hz} corresponds to subject's baseline formant frequency in Hz for the same word (calculated as the median of the subject's last 7 productions of that word in the *baseline* phase). Lastly, each subject's overall change in acoustic speech output in response to the auditory feedback manipulation was quantified by computing an *adaptation index* from the normalized formant frequencies for the last 15 trials (5 trials of each word) in the *full shift* phase of the adaptation task. The adaptation index was based on data averaged across F1 and F2 and across the three test words.

3. Results

3.1 Perceptual ratings of feedback delay

To compensate for any perceptual changes that occur even in the absence of a feedback delay, we first normalized individual subjects' perceptual ratings at each of the seven time points by subtracting the corresponding average responses of the no-delay *Control Group*. The normalized ratings after each 5-minute block of speech production during the *Delay Exposure* task (judgments #1-6) and immediately after the *Auditory-Motor Adaptation* task (judgment #7) are shown in Figure 2. In the following description of these results, all listed *p* values are the adjusted values obtained by applying the Holm-Bonferroni correction method (Holm, 1979) for interpretation against an overall α level of .05 for the family of five tests.

The two groups that did experience a feedback delay during the *Delay Exposure* task (i.e., the two habituation groups) showed a gradual decrease in their judgment of the extent of the delay. In fact, although there was large inter-subject variability, the average rating after just four blocks of speaking indicated no perceived delay at all (i.e., a rating of 0 ms relative to the

Control Group that rated the same feedback signal without exposure to a delay). Thus, subjects in these two groups showed clear evidence of perceptual habituation to the delay across the repeated blocks of speaking, at least in terms of the group average rating. Importantly, the final ratings of both groups indicated that they completed the *Auditory-Motor Adaptation* task also in a perceptually habituated state. The reduction in perceived delay between the first and seventh ratings was statistically significant [$t(21) = 3.483$, $p = .009$] whereas the difference between ratings six and seven was not [$t(21) = 0.660$, $p = .516$].

On the other hand, the subject groups that experienced no delay during the *Delay Exposure* task (the two no-habituation groups) showed little change in their ratings across the initial six speaking blocks and then an increase in their judgment of the delay for the adaptation task (which was the first time these groups were exposed to a delay). Thus, the latter subjects completed the adaptation task in a non-habituated state. Their perceived delay at the seventh rating point was statistically significantly longer than that at both the first rating [$t(21) = -3.496$, $p = .009$] and the sixth rating [$t(21) = -4.791$, $p < .001$]. Moreover, these no-habituation subjects' perceived delay at the seventh rating point (addressing their perception during the adaptation task) was not statistically significantly different from that of the habituation subjects at the very first rating point (when initially exposed to the delay) [$t(42) = 1.227$, $p = .453$].

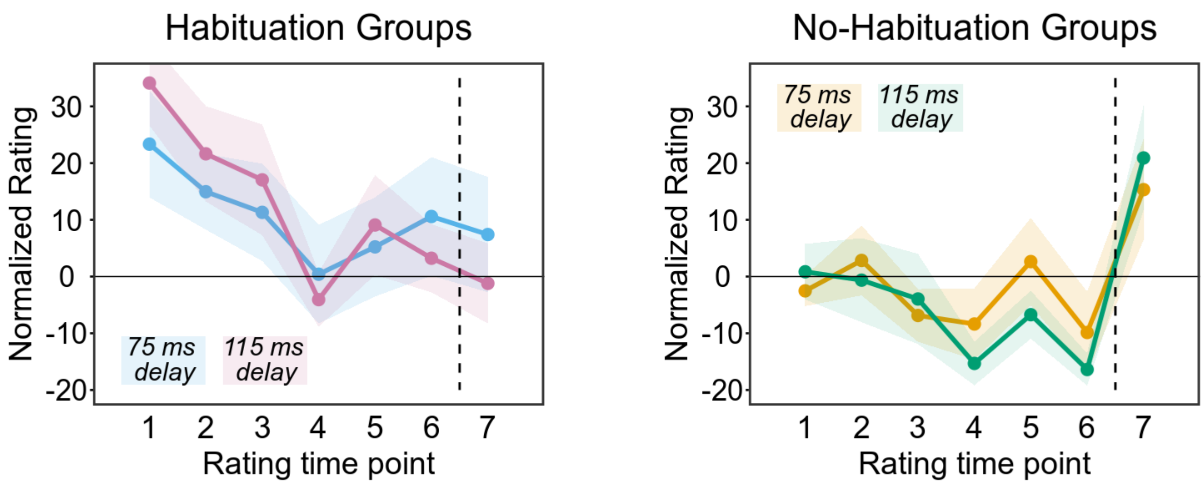

Figure 2. *Normalized group means (with standard errors of the mean indicated by shaded areas) for ratings of perceived auditory feedback delay by the subject groups who experienced a delay throughout the Delay Exposure task (habituation groups, left panel), and the subject groups who experienced no delay during the Delay Exposure task (no-habituation groups right panel). Ratings at time points 1 through 6 were completed during the Delay Exposure task (each rating following a 5-minute block of speaking) whereas the rating at time point 7 was completed immediately following the Auditory-Motor Adaptation task.*

3.2 Auditory-Motor Adaptation task

Participants' adaptation to the formant-shift perturbation manifests itself as a change in the produced vowel formants relative to the baseline phase during which only unperturbed feedback was heard. The analysis approach involved first asking whether or not adaptation did actually occur when feedback was presented with no delay, with a 75 ms delay, and with a 115 ms delay (i.e., changes from baseline within the *Control Group*, *Short-Delay No-Habituation Group*, and *Long-Delay No-Habituation Group*). Next, we determined the effect of feedback delay by asking whether the amount of adaptation in the *Short-Delay No-Habituation Group* and the *Long-Delay No-Habituation Group* was different from the amount observed for the *Control Group*. Lastly, we examined the effect of prior habituation by asking whether the amount of adaptation in the *Short-Delay Habituation Group* and *Long-Delay Habituation Group* was different from that observed in the *Short-Delay No-Habituation Group* and the *Long-Delay No-Habituation Group*, respectively. We considered these statistical tests as one family of three within-group comparisons and one group of four between-group comparisons, and again all *p* values listed below are Holm-Bonferroni adjusted values that are interpreted against a family-wise error rate of $\alpha = .05$.

Data for the no-delay *Control Group,* the *Short-Delay No-Habituation Group,* and the *Long-Delay No-Habituation Groups* are shown in Figure 3. The *Control Group,* which experienced no delay during either the *Delay Exposure* or *Auditory-Motor Adaptation* tasks, started decreasing their produced formants during the ramp shift phase, further decreased these formants throughout the full shift phase, achieved a maximum amount of adaptation of 114 cents (corresponding to 46% of the magnitude of the implemented perturbation), and then gradually returned toward baseline during the after-effects phase, but did not completely reach their baseline performance before the end of the task. This pattern of adaptive changes is fully consistent with previous studies using the same auditory perturbation (Max and Maffett, 2015; Max, Wallace, & Vincent, 2003). Using a one-sample *t*-test comparing the averaged F1 and F2 frequencies at the end of the full shift phase to zero (i.e., the average baseline value), the *Control Group*'s amount of adaptation was statistically significant [$t(10) = -8.727$, $p < .001$]. Overall, the *Short-Delay No-Habituation Group* and the *Long-Delay No-Habituation Group* showed formant production changes in the same direction, and the final amount of adaptation at the end of the full shift phase was also statistically significant for both groups [75 ms group: $t(10) = -4.023$, $p = .004$; 115 ms group: $t(10) = -4.112$, $p = .004$].

However, as is clear from Figure 3, the amount of adaptation across the groups varied with the amount of delay added to the auditory feedback signal. Whereas the final amount of adaptation in the *Control Group* reached 114 cents, in the *Short-Delay No-Habituation* and *Long-Delay No-Habituation* groups it reached only 59 cents and 49 cents, respectively. Using Welch *t*-tests (with adjusted degrees of freedom to account for unequal group variances and with the adjusted *p* values from the Holm-Bonferroni correction), this reduction in auditory-motor adaptation relative to the *Control Group* was statistically significant for both the *Short-Delay Non-Habituation Group* [$t(19.75) = -2.816$, $p = .032$] and the *Long-Delay No-Habituation Group* [$t(19.84) = -3.675$, $p = .006$].

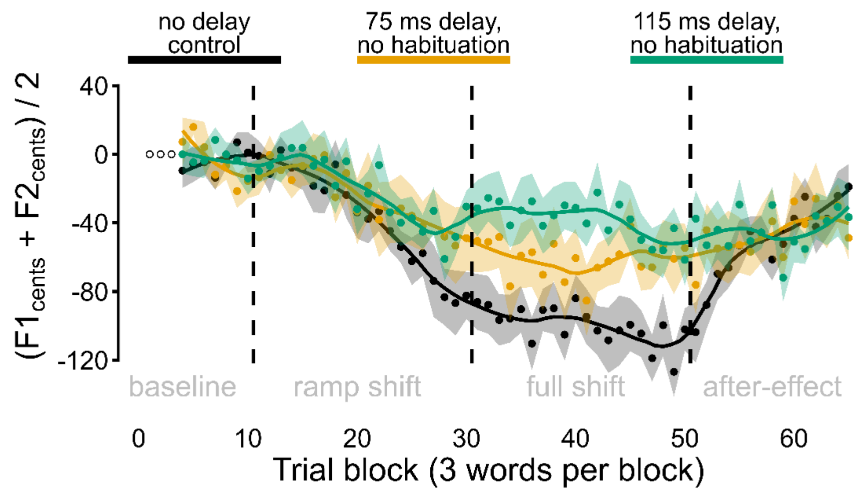

Figure 3. *Speech auditory-motor adaptation to a ramped perturbation that consisted of an upward shift of vowel formant frequencies in the auditory feedback signal (250 cents in the full shift phase). Adaptive changes in the averaged Formant 1 (F1) and Formant 2 (F2) of subjects' productions are calculated in cents relative to the baseline phase during which no formant shift was applied. Data are shown for the Control Group that experienced no feedback delay during either 30 minutes of speaking or the subsequent adaptation task, the Short-Delay No-Habituation Group that experienced no feedback delay during 30 minutes of speaking but a 75 ms feedback delay during the subsequent adaptation task, and the Long-Delay No-Habituation Group that experienced no feedback delay during 30 minutes of speaking but a 115 ms feedback delay during the subsequent adaptation task. Data points represent the group mean formant frequency values for each block of three trials (averaged across F1 and F2); shaded regions show standard errors of the mean; solid lines are loess smoothed fits (span .25).*

Lastly, the effect of 30 minutes of prior feedback delay habituation on the amount of auditory-motor adaptation to the formant shift perturbation was examined for the 75 ms and 115 ms time delays. Figure 4 shows the adaptation time course for the *Short-Delay No-Habituation Group* vs. the *Short-Delay Habituation Group* (top panel) and for the *Long-Delay No-Habituation Group* vs. the *Long-Delay Habituation Group* (bottom panel). Given that one might predict prior delay habituation to reverse the negative effect of such delays on auditory-motor adaptation, the time course of produced formant changes in the no-delay *Control Group* is also shown again for comparison. Despite the fact that 30 minutes of delay exposure had significantly reduced or eliminated the subjective perception of delay in the habituation groups (see perceptual rating results above), these subjects showed no improvement at all in their amount of auditory-motor adaptation as compared with the subjects who had not been previously exposed to the delay. Welch *t*-tests (again with adjusted degrees of freedom and with Holm-Bonferroni adjusted *p* values) confirmed the absence of such an effect for both the 75 ms condition [$t(19.71) = -0.063$, $p = 1.00$] and the 115 ms condition [$t(19.26) = -0.345$, $p = 1.00$]. Thus, prior habituation to the auditory feedback delay did not reduce the negative impact of this delay on the magnitude of the adaptation effect.

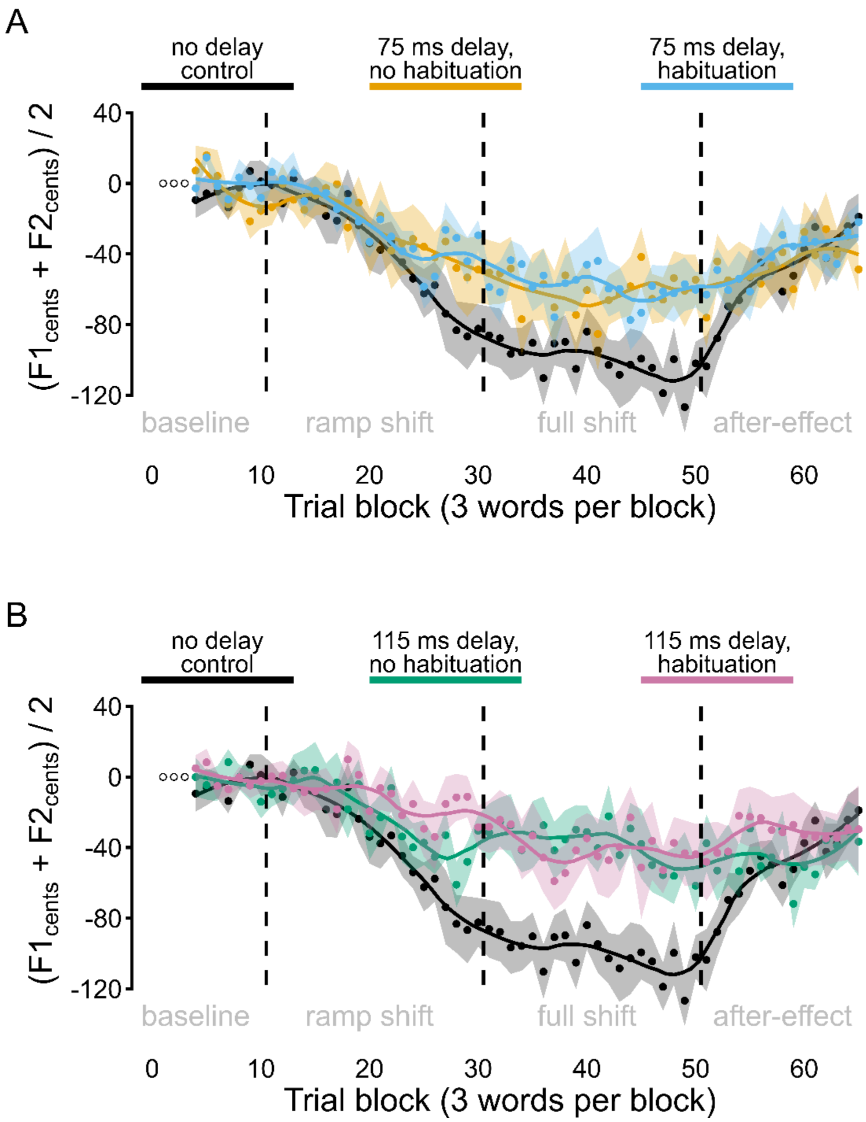

Figure 4. *Speech auditory-motor adaptation to a ramped upward shift (250 cents) of vowel formant frequencies in the auditory feedback signal. A: Comparison of the Control Group that experienced no feedback delay during either 30 minutes of speaking or the subsequent adaptation task, the Short-Delay No-Habituation Group that experienced no auditory feedback delay during 30 minutes of speaking but 75 ms delay during the subsequent adaptation task, and the Short-Delay Habituation Group that experienced 75 ms auditory feedback delay during both 30 minutes of speaking and the subsequent adaptation task. B: Comparison of the same Control Group with the Long-Delay No-Habituation group (no auditory feedback delay during 30 minutes of speaking, 115 ms delay during the adaptation task) and the Long-Delay Habituation Group (115 ms delay during both 30 minutes of speaking and the subsequent adaptation task). Data points indicate group mean formant frequencies for each block of 3 trials (averaged across F1 and F2); shaded areas indicate standard errors of the mean; solid lines are smoothed fit loess functions with span .25.*

4. Discussion

Prior studies on reaching movements have shown that prism or visuo-motor rotation tasks completed with visual feedback delays of 100-5000 ms yield reduced but robust motor learning effects (i.e., statistically significant changes in reach direction during the perturbation phase followed by persisting after-effects during the wash-out phase) (Honda et al. 2012a; Kitazawa et al. 1995; Tanaka et al. 2011). Moreover, related studies have shown that the limited negative effect of a 200 ms visual delay on visuo-motor adaptation can be further reduced through prior exposure to the delay (Honda 2012a, 2012b). For speech movements, on the other hand, prior studies have suggested that even delays as short as 100 ms nearly or completely eliminate auditory-motor adaptation to formant-shifted feedback (Max and Maffett 2015; Mitsuya et al. 2017), and the potential effects of prior delay habituation remain entirely unknown. We therefore investigated whether perceptual habituation to an auditory feedback delay would mitigate the negative effects of such delays on an auditory-motor adaptation task.

In an initial speech production task without formant shift perturbation, two groups of participants spoke for 30 minutes with either short or long feedback delays (75 ms or 115 ms total delay for the *Short-Delay Habituation Group* and the *Long-Delay Habituation Group*, respectively). Participants in both groups showed strong evidence of habituating to the delay, judging the feedback delay to get gradually shorter throughout this 30 minute *Delay Exposure* task and to have almost entirely disappeared by the end of the speaking block. In the subsequent *Auditory-Motor Adaptation* task, the subjects from these two groups remained perceptually habituated to the delay while a formant-shift perturbation was also incrementally added to the auditory feedback signal. Interestingly, these two delay-habituated groups showed no benefit at all in adapting to the formant-shift perturbation as compared with two other, non-habituated groups who had not been previously exposed to the 75 or 115 ms feedback delays that they experienced during the adaptation task. Thus, although we found that perceptual habituation does occur for feedback delays in speech production, we failed to find any evidence for a facilitating effect of such habituation on speech auditory-motor adaptation to a formant-shift perturbation in the presence of feedback delays. All four subject groups that completed the formant-shift adaptation task with a feedback delay (two habituated groups and two non-habituated groups) showed only 40-50% of the extent of adaptation seen in the *Control Group* that completed both the initial 30-minute speaking block and the subsequent adaptation task without any delay added to the auditory feedback. Thus, findings related to the overall extent of adaptation do again confirm that even relatively short feedback delays have substantial detrimental effects on speech auditory-motor adaptation.

It is worth noting that, although delays did have this negative effect on adaptation, the final extent of adaptation achieved by the two 75 ms delay groups as well as the two 115 ms delay groups was larger than that observed in two previous formant perturbation studies with 100 ms delay (Max and Maffett 2015; Mitsuya et al. 2017). Thus, the detrimental effect of auditory feedback delay on speech auditory-motor adaptation was less severe here than in previous studies. The reasons for this finding are unclear, but one obvious methodological difference across studies is that only the participants from the present study first completed a separate block of 30 minutes of speaking before starting the adaptation task, with the exact same instrumentation used for routing auditory feedback in both tasks (recall that the initial speaking task for all participants served to create separate groups that had or had not habituated to the feedback delay, but no formant perturbation was present for any of the groups). Consequently, the extra half hour of speaking in this set-up may have helped participants with getting used to the different sound quality associated with hearing their own speech through insert earphones as opposed to free field air conduction and bone conduction as in typical daily-life speaking conditions. The prior acoustic familiarization, in turn, may have resulted in the neural control system being more sensitive to additional auditory error caused by the subsequent formant perturbation. This interpretation is consistent with the present study's finding that the *Control Group* also showed a final extent of adaptation that is larger (close to 50% of the implemented formant perturbation) than that typically observed in speech production experiments with formant shift perturbations.

Also noteworthy is the overall shape of the learning curve for the *Long-Delay No-Habituation Group* (115 ms delay adaptation task, no prior delay habituation). This group's learning initially aligns very closely with that of the *Short-Delay No-Habituation Group* (75 ms delay adaptation task, no prior delay habituation) but then reverses direction and reflects poorer adaptation throughout most of the perturbation phase, only catching up with the *Short-Delay* group at the very end of the perturbation phase. It could therefore be speculated that a longer delay of 115 ms delay is tolerated just as well as a shorter delay of 75 ms as long as other sensory prediction errors (i.e., reflecting the discrepancies between predicted and heard auditory feedback) are small, but that the combination of longer delay *plus* increasingly large prediction errors results in a disruption of the ongoing learning. This could happen, perhaps, due to credit for the error now being assigned to external sources rather than the self-generated action. However, this idea regarding initial learning in the 115 ms delay non-habituated participants is hard to reconcile with the observation that initial learning in the corresponding habituated participants (*Long-Delay Habituation Group*) does not show such a trend. In fact, taking together the data from both 115 ms delay groups, these participants generally adapted less or, at the very least, took considerably more time to reach the same adaptation level as those experiencing only 75 ms delay.

Our central finding that prior habituation to auditory delays of 75 or 115 ms does not mitigate the detrimental effects of auditory feedback delay on speech auditory-motor learning stands in contrast with Honda's (2012a, 2012b) reports that habituation to visual delays of 260 ms significantly reduces the negative effects of visual feedback delay on visuo-motor learning for reaching movements. Our result is more in line with the earlier conclusion by Tanaka et al. (2011), based on prism adaptation for pointing movements with 136 ms visual delay, that "Physical delay but not subjective delay determines learning rate […]" (p. 257). This is an intriguing result given that our methodology was much more similar to that used by Honda (2012a, 2012b) rather than that of Tanaka et al. (2011): (a) our delay exposure task involved 360 trials (100-120 trials in Honda [2012a, 2012b] vs. only 60 trials in Tanaka et al. [2011]), (b) our auditory formant perturbation was introduced incrementally over many trials (visual perturbations were introduced incrementally in Honda [2012a, 2012b] vs. abruptly in Tanaka et al. [2011]), and (c) we presented auditory feedback throughout the entire word production for each trial (visual feedback reflected the full motion path in Honda [2012a, 2012b] vs. only movement endpoint in Tanaka et al. [2011]).

Hence, the effect of prior delay habituation on sensorimotor learning may be both effector system specific and situation specific. Here, we found that delay habituation had no benefit at all for subsequent speech auditory-motor adaptation with auditory feedback delays even in conditions that had been found to yield a clear delay habituation benefit in the case of reaching movement visuo-motor adaptation (that is, conditions in which full feedback was available during each trial and the perturbation was introduced incrementally across trials). Such differences between speech and limb motor learning in feedback delay sensitivity and delay perception plasticity warrant further research on the generalizability of theoretical perspectives regarding delay representation in neural systems (e.g., the state representation model recently proposed by Avraham et al. 2017) across different sensorimotor domains. For example, it is plausible that, in speech motor control, heightened sensitivity to sensory feedback delays and increased resistance to delay habituation result from fundamental differences in this system's temporal constraints on sensorimotor integration and movement planning. Speech articulation requires the coordination of numerous muscles distributed across and within different effectors (lips, tongue, jaw, velum, larynx) and achieves rates up to 5-6 syllables (or 10-15 individual sounds) per second (Fonagy and Magdics 1960; Levelt 1989; Zemlin 1998). Speech movement durations are often as short as 50-200 milliseconds and movement amplitudes are as small as a few millimeters (Gracco 1994; Max et al. 2003; Ostry and Munhall 1985). Additionally, as a second specific characteristic, the ultimate goals of articulatory movements are sequences of sounds that are intelligible to a listener, and the movements are planned, at least in part, in terms of those acoustic targets (Callan et al. 2000; Feng et al. 2011; Guenther 1994; Guenther et al. 1998, 1999; Lindau et al. 1972; Perkell et al. 1997, 2000). The latter point emphasizes the unique need for the neural controller for speech to take into account not only dynamic and kinematic transformations similar to those involved in limb movements but also additional complex transformations from vocal tract tube shapes and constrictions to the acoustic speech output (Fant 1980; Stevens 2000). Despite subjects' demonstrated capacity for perceptual delay habituation of the acoustic output signal, limitations related to the *physical* delay prevent the neural controller for speech from adjusting sensory predictions to take account of the effect of delay across all the input-output transformations or to increase its reliance on the delayed feedback for adjusting motor commands. Given that habitation did occur, we speculate that the involved sensory predictions were, in fact, appropriately adjusted during the initial delay exposure phase, but that this process nevertheless failed to drive motor learning during the formant perturbation phase.

Importantly, another potential factor that may contribute to the different results obtained here for speech auditory-motor learning as opposed to prior work on reach visuo-motor learning (Honda 2012a, 2012b) is suggested by evidence that speech auditory-motor adaptation is an almost entirely implicit form of learning whereas reach visuo-motor adaptation involves a combination of implicit and explicit components (Anguera et al. 2010; Fernandez-Ruiz et al. 2011; Holland et al. 2018; McDougle et al. 2016; Taylor et al. 2014). Indeed, several studies on speech sensorimotor learning have demonstrated that subjects are unaware that they made any changes in their speech output in the presence of the perturbation, and that there is no difference in the extent of adaptation when subjects are instructed to ignore the feedback or to avoid compensating for the perturbation (Keough et al. 2013; Kim and Max 2020; Munhall et al. 2003). In light of recent findings that delayed feedback may negatively affect implicit learning without much impact on explicit strategy selection (Brudner et al. 2016; McDougle and Taylor 2019; Schween and Hegele 2017), speech auditory-motor learning may be resistant to the benefits of prior delay habituation due to being largely implicit in nature (Keough et al. 2013; Kim and Max 2020; Munhall et al. 2003). By purposefully designing new speech auditory-motor learning paradigms that depend to varying degrees on implicit vs. explicit learning, future studies might be able to directly test this hypothesis.

In sum, the present study identified a substantial decrease in speech auditory-motor learning when auditory feedback was delayed by 75 or 115 ms. Even though a preceding half hour of delay exposure led to perceptual habituation to the delay, such prior exposure yielded no benefit in a subsequent adaptation task in which a formant shift perturbation was added to the delayed auditory feedback signal. Thus, we conclude that such short-term habituation to auditory feedback delay is not effective in reducing the negative impact of delay on speech auditory-motor adaptation. We further hypothesize that this finding likely results from fundamental differences in control requirements for the speech and reach effector systems or from different contributions of implicit and explicit learning mechanisms when these effector systems adapt to perturbed feedback signals.

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