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Feedback Schedule Effects on Speech Motor Learning in Older Adults

RESEARCH

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ABSTRACT

Purpose: The Principles of Motor Learning (PML) emerged from studies of limb motor skills in healthy, young adults. The applicability of these principles to speech motor learning, and to older adults, is uncertain. The purpose of this study was to examine one PML, feedback frequency, and to elucidate whether it affects the retention of a speech motor task.

Method: Thirty older participants were randomly assigned to one of the three feedback frequency groups (every trial, every 5th, every 10th) and trained to produce a phrase 2 times and 3 times slower than their habitual rate. Over 100 practice trials, all participants demonstrated a reduction in error, suggesting they understood and acquired the task. Mean absolute error (MAE) was measured to examine delayed 2- to 4- day retention.

Results: When participants returned for retention testing 2 to 4 days post-training, those receiving feedback every 5th trial demonstrated significantly lower MAE (enhanced retention) compared to those receiving high frequency feedback following every trial. There were no significant differences between participants receiving feedback following every trial or every 5th trial versus every 10th trial.

Conclusions: Enhanced retention of the trained speech motor task for participants receiving low frequency feedback following every 5th trial, relative to those receiving high frequency feedback following every trial, is consistent with the extensive limb motor learning literature and the trend of a small number of speech motor learning studies, suggesting provision of low frequency feedback enhances retention of trained novel movements.

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INTRODUCTION

The Principles of Motor Learning (PML), and their application to the training of motor movements related to speech production, remain of great interest to the field of Speech-Language Pathology (SLP) (Bislick, Weir, Spencer, Kendall, & Yorkston, 2012; Maas, Robin, Austermann-Hula, Freedman, Wulf, Ballard, & Schmidt, 2008). PMLs are a set of processes associated with practice or experience, leading to relatively permanent changes in the capability for movement (Schmidt et al., 2019). These principles can be divided into variables related to the structure of practice and to the nature of feedback. Principles relating to the structure of practice pertain to how a training session is implemented, considering conditions such as practice amount (e.g., low versus a high number of practice trials), options regarding blocked vs. random presentation of training targets, complexity of training targets, and so forth. Principles related to the nature of feedback, on the other hand, pertain to information provided after the completion of a movement. This information can be provided in rich or limited detail, with varied frequency (e.g., following every trial versus every fifth trial, etc.), immediately following the movement, or after a brief delay (e.g., five seconds). Implementing PMLs when training skilled movements has considerable implication for an individual's ability to learn and retain those movements (Schmidt et al., 2019). While the use of these principles is well established in the limb literature (Winstein & Schmidt, 1990; Sparrow & Summers, 1992; Vander Linden, Cauraugh, Greene, 1993; Weeks & Kordus, 1998; Wulf, Shea, & Matschiner, 1998), their applicability to motor learning in speech remains unclear.

While a wealth of limb studies have demonstrated the effectiveness of PMLs to enhance retention of trained limb movements, to date, few studies have investigated the application of PMLs to speech in healthy young adults (Adams & Page, 2000; Jones & Croot, 2016; Kim, LaPointe, & Stierwalt, 2012; Lowe & Buchwald, 2017; Steinhauer & Grayhack, 2000), healthy older adults (Kaipa, Robb, & Jones, 2017; Weir-Mayta, Spencer, Bierer et al., 2019), and those with acquired motor speech disorders in adults (Adams et al., 2002; Austermann et al., 2008; Ballard, 2001; Bislick et al., 2012; Johnson, 2018; Johnson, Lasker, Stierwalt, MacPherson, & LaPoint, 2018; Johnson, Lott, & Prebor, 2018; Wambaugh et al., 2013, 2014, 2018, 2020). Although differences between the neural circuitries of limb and speech exist (e.g., complexity and fast rate of articulation, no visual feedback from structures involved during speech, etc.), enough similarities in the requirements for movement planning, trajectory, timing, coordination, sequencing, and biomechanics (Grimme, Fuchs, Perrier, & Schoner, 2011) are present that may extend the applicability of PMLs to facilitate motor learning in speech as well. However, while results of some of these studies support the use of PMLs to enhance speech motor learning, similar to studies in the limb literature, others have produced unexpected outcomes, highlighting the potential issues with generalizing the PML to other modalities and populations. Thus, the suitability of applying the PML to speech remains under investigation in the field.

The current study focuses specifically on one PML, feedback frequency, in older, healthy adults using a speaking rate-matching paradigm (Adams & Page, 2000; Adams et al., 2002; Bislick et al., 2013; Weir-Mayta et al., 2019). Gaining a clearer understanding of how feedback frequency influences speech motor learning in healthy older adults can help form a foundation for future studies exploring its use in the neurologically impaired population (e.g., individuals with Parkinson's disease).

BACKGROUND

Schema Theory: At the center of theories of motor learning is the concept of schema theory (Schmidt, 1975, 2003; Schmidt & Lee, 2019; Sherwood & Lee, 2003). This theory has been a mobilizing force in the study of motor learning in the non-speech arena for decades. The theory proposes that motor programs do not contain the specifics of movements, but instead comprise "generalized" rules governing a specific class of movements. First used in the field of psychology, the term "schema" refers to an abstract representation stored in memory following multiple experiences (Schmidt, 1975). These motor programs can be retrieved from memory and adapted depending on any given situation. When presented with a new motor skill, an individual learns the new motor program as a set of generalized rules or abstract representations of the basic movement pattern that can be applied to a variety of contexts. Given that a movement is never produced the exact same way each time, schemas contain

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the rules for creating the spatial and temporal patterns of muscle activity needed to carry out the given movement, referred to as a generalized motor program (GMP) (Schmidt & Lee, 2019). More specifically, GMPs are abstract movement patterns that specify relative timing and relative force of muscle contractions, whereas the absolute timing and force are specified by various situational parameters (Schmidt, 1975; Schmidt & Lee, 2019; Maas et al., 2008). In speech movements, GMPs are articulatory specific, where abstract phonological symbols are assigned properties (i.e., place and manner of articulation) amenable to a motor code (Van der Merwe, 1997, 2009, 2020), such as, for example, the motor commands associated with phoneme or syllable productions (Maas et al., 2008; Varley, Whiteside, Windsor, & Fisher, 2006); conversely, speech parameters are muscle specific where specifications regarding muscle tone, direction, velocity, force, range, and mechanical stiffness of joints are delineated (see Van der Merwe, 2020).

During the acquisition of a new motor skill, GMPs must encode the relationships among initial conditions, the sensory consequences of the movement, and the movement's outcome. Upon completion of the movement, the motor system compares the movement goal with its outcome. If the recognition schema detects a mismatch between the actual sensory consequences and the expected sensory consequences of a correct movement, an error signal is generated and used to update the recall schema for future trials. In speech, production of a new sound (speech motor movement) relies heavily on the auditory feedback control subsystem to repeat the sound presented. When a sound is heard, it takes the form of time-varying acoustic signals corresponding to a phoneme, syllable, or word spoken by a human speaker. Thus, learning new sounds requires activation of an auditory target or goal in auditory cortical areas. Later, the motor commands required to attempt the target sound are activated. Following execution (production) of the sound, if a mismatch occurs between the auditory and somatosensory target, the expected tactile and proprioceptive sensations associated with the sound, the motor command can be updated for subsequent attempts (Guenther 2006; Tourville and Guenther, 2011). With repeated practice for both limb and speech movements, performance improves due to lessening of the gap between actual sensory consequences and expected sensory consequences. This allows for an accurate internal representation—or "model"—of the movement, and thereby represents a successful learning paradigm. Thus, when a new movement is being learned, be it a limb or speech movement, the structure of practice and type of feedback provided can have important implications regarding the efficiency at which the internal model is constructed and the long-term retention of the acquired movement.

Internal Models: The process of detecting and correcting errors allows neuroanatomical mechanisms to develop an accurate internal model of the movement being taught. Shadmehr and Krakauer (2008) detail a computational neuroanatomy model for voluntary movements and learning. In their model, they explain how various motor structures are involved in the movement and learning processes: The cerebellar cortex builds internal models that predict sensory outcomes of motor commands and correct errors via internal feedback, while the motor cortex implements an optimal control policy by transforming beliefs about sensory states into motor commands. Elements of this comprehensive model can be seen in the frameworks of other models of limb and speech motor learning and production, such as internal models of the cerebellum and the Directions into Velocities of Articulators (DIVA) model of speech production (Guenther, 2006; Tourville & Guenther, 2011).

When sensory information regarding accuracy of movement outcome is limited or unavailable internally, external feedback from an instructor becomes crucial in establishing accurate internal models. This is applicable to speech motor learning given that, unlike visual feedback available during limb movement, speech movements rely heavily on auditory and somatosensory feedback to shape the accuracy of articulatory movements. While each PML can enhance the learning of skilled movements, evidence from limb studies has demonstrated the importance of feedback, with the frequency at which it is provided being of paramount importance for long-term retention (Schmidt et al., 2019). Specifically, a relatively low-frequency feedback schedule, where feedback information is provided after a relatively small percentage of trials (e.g., 20%, 50%, etc.), results in slower acquisition but enhances retention (Winstein & Schmidt, 1990; Sparrow & Summers, 1992; Vander Linden et al., 1993; Weeks & Kordus, 1998). Conversely, high-frequency feedback, where feedback information is provided after a high percentage of trials—perhaps even after every trial—quickly guides the learner to accurate performance during acquisition of the skill, but degrades retention of the learning (Salmoni et al., 1984; Schmidt, 1991).

According to the guidance hypothesis (Salmoni et al., 1984; Schmidt, 1991), when feedback is provided too frequently, the learner may become reliant on the external guidance and fail to process internal information necessary for encoding of the movement. On the other hand, when feedback is provided less frequently, the learner must detect and correct errors independently, thus facilitating the use of effective strategies that aid in accurate completion and recall of the skilled movement (Schmidt et al., 2019). Given the robust evidence for the effectiveness of low-feedback frequency, several studies have examined the effect of feedback frequency on the learning of novel speech movements in healthy adults (Adams and Page, 2000; Kim et al., 2012; Lowe & Buchwald, 2017; Steinhauer & Grayhack, 2000; Weir-Mayta et al., 2019). However, the results are not conclusive enough to establish specific guidance related to new treatment protocols for motor speech disorders, highlighting a need for more research on the topic.

In 2000, Adams and Page compared the effects of feedback after every trial versus every 5th trial utilizing 20 healthy, young female participants (ten participants per group). The participants were instructed to "slow their rate down" while producing the phrase "Buy Bobby a poppy" with a duration of 2400 milliseconds (approximately two times slower than typical speaking rate). The practice amount was set at 50 trials per group, and participants received visual feedback via graphing paper showing their production in comparison to the target rate (i.e., absolute error). As predicted, when participants returned 2 days post-training for retention testing, those receiving low-frequency feedback (following every 5th trial) showed lowered mean absolute error (i.e., enhanced retention). Similar speech motor learning benefits from a reduced feedback frequency were reported later by Steinhauer and Grayhack (2000).

In 2012, Kim and colleagues examined the effect of manipulating several parameters of motor learning theory on participants' phonetic acquisition and retention of utterances in a foreign language (Korean). Thirty-two healthy, native English-speaking participants with no prior exposure to a foreign language were each given 10 Korean sentences to practice. Participants were randomly assigned to one of four groups examining practice amount (25 trials vs. 100 trials) and feedback frequency (every 5th trial vs. every trial). Participants listened to and repeated the sentences delivered by a native Korean speaker and were provided feedback (positive, neutral, or negative) according to their assigned schedule. Outcome measures included speech intelligibility, speech naturalness, and speech precision judged by a panel of 21 native Korean speakers blinded to training conditions. In both a 1-day and 1-week retention test, the group who received 100 practice trials and feedback after every 5th trial significantly outperformed all other groups. While these findings are encouraging—in addition to being consistent with previous findings on the effect of feedback frequency on retention, they also provide support for using a larger practice amount when training a novel speech phrase—results from other studies have been less conclusive, highlighting a need for additional research.

In 2017, Lowe and Buchwald found inconclusive results regarding the benefits of a reduced feedback schedule. In their study, the researchers randomly assigned 32 young healthy adults into one of four feedback frequency groups: 100%, 50%, 20%, or 0%. Participants were asked to practice eight novel nonwords 10 times and received feedback per assigned schedule. Retention testing took place 30 minutes (short-term retention) and 2 days (long-term retention) after training. Results showed no effect of frequency on speech motor learning of nonword accuracy, phoneme accuracy, or acoustic measures. As the authors explain, one possible reason for this null effect may relate to practice amount and task complexity. Motor learning studies have demonstrated that large amounts of practice with complex targets are beneficial for retention of newly learned motor skills (Maas et al., 2008). The practice amount in Lowe and Buchwald's study (10 times) is a small number compared to other speech motor learning studies (40 to 100 times; Adams & Page, 2000; Kim et al., 2012; Steinhauer & Grayhack, 2000).

Similarly, in a 2019 study, Weir-Mayta and colleagues found no effect of feedback frequency on the retention and generalization of a novel speech task. In their study, the researchers had sixty healthy older adults practice the phrase, "Buy Bobby a poppy" at speaking rates 2x and 3x slower than their habitual rate. In addition to the speech task, Weir-Mayta and colleagues had participants complete a limb motor learning task requiring the tracing of a sine wave 2x and 3x

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slower than their habitual rate. The phrase and arm tasks were practiced over 60 randomized trials each (30 trials at the 2x slower rate and 30 trials at the 3x slower rate). Participants were randomly assigned to receive visual feedback on their accuracy immediately following every trial, every 5th trial, or every 10th trial. MAE was measured to examine immediate generalization, delayed generalization, and 2- to 4-day post-training retention. Results suggest that feedback frequency has no effect on the generalization or retention of either task. Similar to Lowe and Buchwald's (2017) study, the authors note that 60 practice trials in total, 30 per task, may have been insufficient to allow participants to build a stable internal model of the motor skills.

In addition to amount of practice, age is an important variable to consider when examining speech motor learning. In the broader gerontology and limb motor learning literature, it is well established that age-based learning differences exist and must be considered when training older individuals (King et al., 2013; Rodrique et al., 2005; Seidler et al., 2010; Voelcker-Rehage, 2008). Moreover, age interacts with practice to affect learning and retention. Specifically, older adults often need additional practice trials to achieve motor results similar to their younger counterparts (Voelcker-Rehage, 2008), while younger adults produce faster and more consistent movements and retain trained tasks better than older adults (Schulz, Stein & Micallef, 2001; Sadagopan & Smith, 2013). These learning and retention differences are due to changes in dopamine levels within the striatal networks as we age, which can significantly alter and contribute to greater variability in the process of learning speech sequences (Aizenstein et al. 2006), hence their poorer performance relative to the young participants. Similarly in the neurologically impaired population, individuals with Parkinson's disease have retention deficits of newly acquired speech motor skills (Whitfield & Goberman, (2017), due to pathology in the sensorimotor region of the basal ganglia (Debas et al., 2014). Thus, these pathological changes seen in healthy older adults may account for the lack of frequency effects observed in Weir-Mayta et al.'s (2019) study, given that their participants were older than those in other studies that found the expected frequency effects.

RATIONALE OF THE STUDY

While established in limb motor learning, in accordance with schema theory and the guidance hypothesis, the role of feedback frequency in speech motor learning remains unconfirmed, particularly in older populations. Schmidt's schema theory (1975) posits two components of motor control: recall schema (movement rules based on past experiences) and recognition schema (judgment regarding accuracy of the target movement). In the context of motor learning principles, increasing practice amount allows more opportunities to establish relationships amongst various components associated with each movement, which in turn enhances the stability of recall and recognition schemas (Maas et al., 2008). The guidance hypothesis postulates that low-frequency feedback allows for improved detection and correction of errors, allowing for accurate development of recognition schemas that can be used effectively when the feedback is withdrawn (Maas et al., 2008; Winstein & Schmidt, 1990). If PMLs are to be useful in the treatment of motor speech disorders, then it is first necessary to gain a clearer understanding of how each principle, or a combination of principles, enhances the retention of motor skills in neurologically healthy populations.

Utilizing work from Adams and Page (2000) and Weir-Mayta et al. (2019), an established speech paradigm was used in the present study that entailed having older participants practice the phrase "Buy Bobby a poppy" at rates two times (2x) and three times (3x) slower than habitual rates for a total of 60 trials (30 at the 2x slower rate and 30 at the 3x slower rate). Randomizing of the two different rates during practice (2x and 3x slower) was selected given supportive evidence from work on both limb (Lee & Magill, 1983; Lee et al., 1985; Shea & Kohl, 1991; Schmidt & Bjork, 1992; Shea & Morgan, 1979; Wright et al., 2004; Wulf & Lee, 1993) and speech movements (Adams & Page, 2000; Jones & Croot, 2016; Kaipa, Robb, & Jones, 2017; Knock et al., 2000) that a randomized practice schedule enhances retention over that of blocked practice. The learning enhancing effects of random practice stems from findings exploring the elaboration and distinctiveness hypothesis (Shea & Morgan, 1979), where the trial-to-trial comparisons of movement goals and movement outcomes help to improve accuracy of the internal model. Additionally, the action plan reconstruction hypothesis (Lee & Magill, 1983, 1985) postulates that before a movement occurs, an "action plan" must be prepared. In blocked practice, a previously prepared "action plan" is readily available from trial to trial, but it suffers from lack of attention on following trials interfering with encoding of the skilled movement. However, during random practice, each time a task must be executed, a "reconstruction" of the plan must be processed from trial to trial. This allows information regarding the movement to remain in working memory longer, resulting in a more resilient memory representation that supports long-term recall efforts over that of blocked practice (see Magnuson & Wright, 2004).

We maintained the phrase and randomized practice schedule and increased the total number of practice trials (i.e., practice amount) to 100 (50 at the 2x slower rate and 50 at the 3x slower rate) for the speech task in alignment with Kim and colleague's findings (2012). The arm and generalization tasks were eliminated. Thus, the current study was designed to examine the effect of feedback schedule (every trial, every 5th trial, every 10th trial) on the ability of neurologically healthy older adults to learn a speech motor task. Maintenance of learning was measured via retention testing 2 to 4 days post-training during which no feedback was provided. This range was determined in agreement with previous similar speech motor learning studies investigating feedback frequency (Bislick et al., 2013; Weir-Mayta, et al., 2019). We hypothesized that optimal learning would be achieved with low-frequency feedback provided every 5th and/or every 10th trial, analogous to the majority of extant limb and speech motor learning studies in young adults.

METHODS

PARTICIPANTS

Participants were provided informed consent before study participation in accordance with the Institutional Review Board of California State University, Fullerton. Thirty healthy older adults, with a mean age of 62.9 years (range 50–81 years), and a mean education of 15.8 years (range of 12–20 years; see Table 1) were randomly assigned to one of three groups (n = 10) receiving feedback every trial, every 5th trial, or every 10th trial. One-way between-subjects ANOVAs revealed no significant differences in age [$F(2,27) = 0.1254$, $p = .883$] or years of education [$F(2,27) = 0.1265$, $p = .882$] across conditions.

Table 1 Participant characteristics including mean and standard deviations for age, education, and habitual speaking rate.

Note: Group differences between habitual speaking rates were non-significant *(p > .05).*

FEEDBACK GROUP	EVERY TRIAL (SD)	EVERY 5TH (SD)	EVERY 10TH (SD)
Total Participants	10	10	10
Gender	7 F	7 F	9 F
	3 M	3 M	1 M
Age	61.8 (11.50)	62.7 (10.89)	64.1 (8.40)
Education (years)	15.6 (2.41)	16.1 (2.85)	15.7 (1.64)
Habitual Speaking Rate (ms)	1375.3 (252.23)	1414.3 (214.64)	1351.0 (217.78)

All participants were required to be native speakers of American English; to have adequate visual acuity, hearing thresholds (≤50 dB at 500, 1000, and 2000 Hz), and typical speech, language, and cognitive developmental history; and to successfully pass a depression (<24 on the *Beck Depression Inventory II*; Beck, Steer, & Brown, 1996), language (above the 85th percentile on combined subtests of the *Boston Diagnostic Aphasia Exam* (Commands and Complex Ideational Material; Goodglass & Kaplan, 2001), and cognitive screening (≥25 on the *Mini-Mental Status Exam*; Folstein, Folstein, & McHugh, 1975). Out of the original 34 participants recruited, one was excluded due to failing the hearing screening and three were excluded due to difficulty learning the task (e.g., unable to understand feedback graph during pre-practice phase).

PROCEDURES

The experiment consisted of two phases. Phase I involved screening, pre-practice, and acquisition (training) of the speech task. Pre-practice was intended to prepare the learner for the acquisition training session, ensuring proper motivation to learn, an adequate understanding of the task, and that participants know how to perform the task correctly to avoid any frustration due to inability to produce the intended target (Maas et al., 2008; Schmidt et al., 2019). Phase

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II occurred two to four days post-training (Bislick, et al., 2013; Weir-Mayta et al., 2019) and involved retention measurement of the speech task with no feedback provided.

Phase I: Participants who met all selection and screening criteria were randomly assigned to one of three groups—feedback every trial, every 5th trial, or every 10th trial—with 10 participants in each group. Participants were seated in front of a computer monitor; the examiner sat beside the participant at a computer running a custom written program using Python (2017). During the *pre-practice phase*, the participants were oriented to the visual feedback display following two demonstration trials performed by the experimenter.

To obtain the participant's habitual rate for the speech task, each speaker was directed to say the target phrase, "Buy Bobby a poppy" (Adams & Page, 2000; Adams et al., 2002; Bislick et al., 2013; Weir-Mayta et al., 2019) 10 times at their normal speaking rate. Results were digitally recorded, and the duration of each production was determined with software custom-written in Python. Results were then instantaneously averaged, plotted on a graph, and displayed on the participant's monitor. Three color-coded lines appeared on the graph, one at the participant's habitual duration (the average of the 10 trials), one at a duration twice as long (2x), and one at a duration three times as long (3x). The participants were then instructed to slow their rate of production and complete four practice trials (2 per target rate) attempting to match the 2x slower and 3x slower target durations. Participants were instructed to say the entire phrase in one breath, elongating the vowels, as modeled by the experimenter (Adams & Page, 2000; Adams et al., 2002; Bislick et al., 2013; Weir-Mayta et al., 2019). A one-way between-subjects ANOVA results revealed no significant difference in habitual speaking rate across conditions, [$F(2,27) = 0.1947$, $p = .824$] (Table 1).

Upon completion of the pre-practice phase, participants began the *acquisition phase* during which they completed 50 trials attempting a 2x slower target duration and 50 trials attempting a 3x slower target duration for a total of 100 acquisition trials (Kim et al., 2012). Target durations were randomly presented by the computer program. To inform the participant of the target rate, the label "2x" or "3x" was displayed on the monitor before the initiation of a trial and remained throughout trial execution. The duration of the participant's phrase production was displayed on the screen relative to the color-coded target duration line to provide visual feedback regarding the accuracy of the attempt (see Figure 1 for an example). One group of participants received such feedback after every trial (high-frequency condition), one group received summary feedback after every 5th trial (i.e., all preceding 5 targets were provided simultaneously on the display; low-feedback condition), and one group received summary feedback after every 10th trial (low-feedback condition). No verbal feedback was provided by the examiner, thereby reducing potential experimenter bias effects.

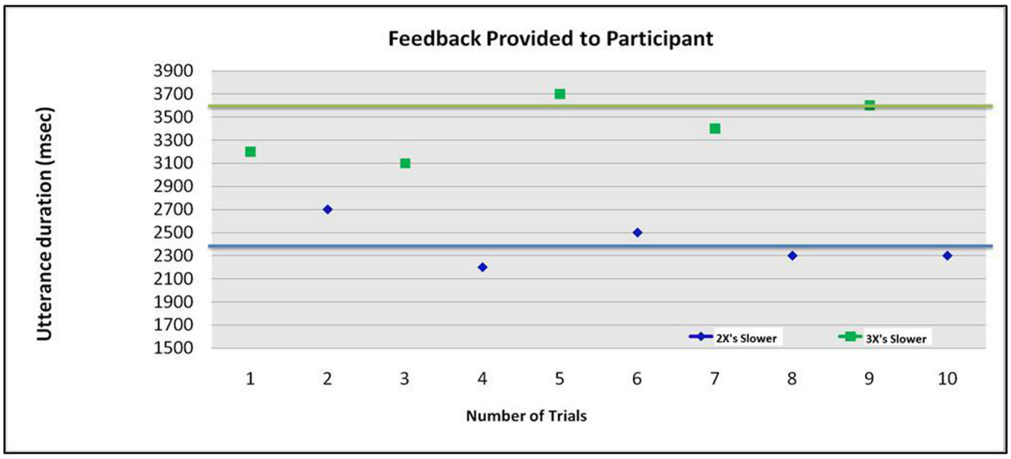

Figure 1 Example of a visual feedback graph for the first 10 trials, provided to participants in the feedback every trial condition. Data represent recorded duration and distance (error) from the target duration; the colored coded lines—blue for "2x" slower and green for "3x" slower—represent the target durations participants are trying to match. The closer a data point is to the target duration line, the more accurate (less error) their production. To limit the usable amount of feedback provided, utterance duration rates in milliseconds along the *y*-axis were not visible to participants.

Phase II. Participants returned 2 to 4 days post-training for retention testing. Subjects completed 50 randomized trials of the speech task (25 trials with the 2x slower target and 25 trials with the 3x slower target); however, no feedback display was provided. As with prior studies, participants were not refamiliarized with the slowed speech rate matching task prior to retention testing (Adams & Page, 2000; Adams et al., 2002; Bislick et al., 2013; Kim et al., 2012; Lowe & Buckwald, 2017; Weir-Mayta et al., 2019). See Table 2 for a summary of the experimental paradigm.

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	PHASE I			PHASE II
	Habitual Rate	Pre-practice Phase	Acquisition Phase	Retention Testing of Trained Task
Speech Task	"Buy Bobby a Poppy"			"Buy Bobby a Poppy"
	10 trials	4 trials total:	100 trials total:	50 trials total:
		2 at 2x slower	50 at 2x slower	25 at 2x slower
		2 at 3x slower	50 at 3x slower	25 at 3x slower

Table 2 Speech and task conditions for Phase I and Phase II of the experiment.

INSTRUMENTATION

To present and analyze parameters of the speech task, custom software written in Python programming environment was employed. It consisted of two graphical user interfaces: a single control window for the setting of parameters by the experimenter, and one separate "subject interaction" window for the speech task. The software was designed to run on a dual-monitor setup, such that the control panel was continuously visible to the experimenter on one monitor, while the interaction panel for the speech task was presented on a full screen to the participant on the other monitor. Feedback was presented graphically to the subject within the interaction window and mirrored to the control panel as text. To capture and record speech productions, a head-worn microphone (AKG Pro Audio CM311 AESH SHURE) was connected to the desktop via an audio interface. Microphone-to-mouth distance was held constant at 2 inches. The audio interface was connected via USB cable to the experimenter's computer running the Python program. Microphone gain setting was consistent across participants.

STATISTICAL METHODS

This study sample size was determined in congruity with previous similar speech motor learning studies investigating feedback frequency (Adams & Page, 2000; Steinhauer & Grayhack, 2000; Kim et al. (2012). A power analysis (Cohen, 1988, 1992) was performed using GPower 3.1.9.2 software (Faul et al., 2007, 2009) for detecting an omnibus effect in an ANOVA (i.e., Feedback 1, Feedback 5, Feedback 10). A priori power was evaluated by estimating the minimum detectable effect size (Kraemer et al., 2006). Traditional criteria were assumed ($p < .05$; two tailed; power = 80%; Cohen's effect size guidelines, e.g., $d = 0.2$, 0.5, and 0.8 for small, medium, and large effects respectively). Applying Adams and Page's (200) effect size of $d = 0.123$ to the present study, we found that the chance of detecting a similar mean difference with $n = 10$ per condition was >99.9%.

Mean absolute error (MAE) was the dependent variable used to measure deviation from the target duration (i.e., a lower score indicates productions close in duration to the target duration). A preliminary ANOVA revealed no significant main effect or interactions involving target rate conditions; thus, the 2x and 3x rates were collapsed and used for final analysis. An ANOVA was then conducted to examine the impact of feedback condition on 2- to 4-day retention of the speech task. For data analysis, significance was set at $\alpha = 0.05$ (Dahiru, 2008; McLeod, 2019; Olsson-Collentine et al., 2019; Pritschet et al., 2016; Sullivan & Feinn, 2012; Yoder et al., 2018).

RESULTS

RELIABILITY

To test reliability of speech duration measurements calculated by the Python software, the intra-class correlation coefficient was computed to assess actual measurements of sound segments captured in Python and blind comparison ratings from two research assistants using Adobe Audition. Random durations from 30% (30/100) of the total acquisition speech trials per individual were calculated. Results revealed a strong absolute agreement between the three rating systems, using the two-way random effect models and "single rater" unit, kappa = 0.966, $p < .001$. We therefore conclude that there exists a strong agreement between the measurements of sound segments captured in Python and rating from two research assistants using Adobe Audition.

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ACQUISITION

Baseline Performance (trials 1–10): To determine if any group differences in MAE were present at baseline during the first ten acquisition trials (the first 10 per participant out of 100 total trials), a one-way between-subjects ANOVA was conducted. Results revealed there was no significant effect of feedback frequency on MAE across conditions, [$F(2,27) = 1.01$, $p = .367$] (see Figure 2).

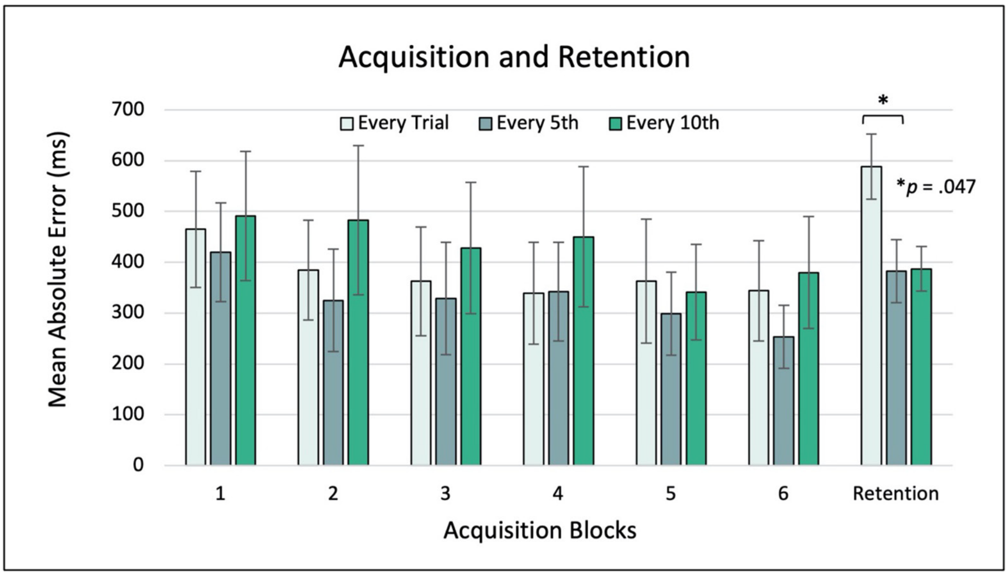

Figure 2 Mean absolute error and standard deviations for acquisition blocks 1–6 and the speech task across retention. Error bars represent standard error of the mean. Blocks 1 & 6 represent the first and last 10 practice trials per group. Blocks 2–5 contain 20 practice trials per group.

Performance During Acquisition (trials 1–100): To verify that the 100 acquisition trials were effective and that participants learned the task, within-subject *t*-tests were conducted comparing the MAE for the first 10 trials at the combined 2x and 3x target rates with the last 10 trials of the combined 2x and 3x target rate, per feedback group. Results indicated that MAE decreased significantly in all conditions (Feedback 1 $p = .011$; Feedback 5 $p = .001$; and Feedback 10 $p = .005$), suggesting an overall pattern of acquisition (see Table 3).

FEEDBACK CONDITION	FIRST BLOCK MAE (SD)	LAST BLOCK MAE (SD)	*T*	*P*
1	465.03 (363.07)	344.28 (314.36)	2.592	.011
5	419.83 (308.88)	253.28 (196.42)	4.75	.001
10	491.18 (401.59)	380.23 (348.69)	2.87	.005

Table 3 Within-subject *t*-test results comparing Mean Absolute Error (MAE) and Standard Deviation (SD) of the first 10 acquisition trials for the combined 2x and 3x target rates (First Block) to the last 10 acquisition trials for the combined 2x and 3x target rates (Last Block) per feedback group.

To identify if any performance differences were present over the total 100 acquisition trials per group, a one-way ANOVA was conducted examining performance across the different conditions (every trial, every 5th, every 10th). The results revealed no statistically significant difference ($F(2, 27) = 0.897$, $p = .420$), indicating that the performance for the every trial condition ($N = 10$, $M = 370.91$, $SD = 165.13$) is comparable to the performance for every 5th trial condition ($N = 10$, $M = 348.26$, $SD = 103.80$) and that for the every 10th trial condition ($N = 10$, $M = 439.87$, $SD = 195.23$) during acquisition.

Final Performance (trials 91–100): Using the last 10 trials of the combined 2x and 3x rates, a one-way between-subjects ANOVA compared the effect of feedback frequency on acquisition for the every-trial, every-5th-trial, and every-10th-trial conditions. There was a significant effect of feedback frequency on MAE across conditions ($F(2,27) = 4.960$, $p = .008$). *Post hoc* comparisons (see Figure 2) using the Tukey HSD Test for multiple comparisons found that the mean value for feedback every 5th trial ($M = 253.28$, $SD = 196.42$) was significantly lower (more accurate) than for every 10th trial ($M = 380.23$, $SD = 348.69$, $p = .007$; $d = 0.44$) and marginally different than for every trial ($M = 344.28$, $SD = 314.36$, $p = .074$, $d = 0.38$). The effect sizes for these analyses ($d = 0.44$; $d = 0.38$) exceed Cohen's (1988) convention for a small effect ($d = 0.2$). There was no significant difference between the every-trial and every-10th-trial condition.

RETENTION

The mean and standard deviations of when participants returned for retention testing (2, 3, or 4 days post-training) were similar across groups (Feedback 1 $M = 2.2$, $SD = 0.4$; Feedback 5 $M = 2.3$, $SD = 0.46$; and Feedback 10 $M = 2.4$, $SD = 0.66$). A one-way between-subjects ANOVA compared the effect of feedback frequency on retention (as measured by MAE), finding a significant effect of feedback frequency on MAE across conditions, $F(2, 27) = 4.089$, $p = .028$. *Post hoc* comparisons (See Figure 2) using the Tukey HSD Test for multiple comparisons found that the mean value for every trial ($M = 588.32$, $SD = 203.85$) was significantly higher (less accurate) than for feedback every 5th trial ($M = 383.44$, $SD = 199.29$), $p = .047$, $d = 1.02$. The effect size for this analysis ($d = 1.02$) exceeds Cohen's (1988) convention for a large effect ($d = .80$) and the observed statistical power (SP) in our sample size supported the statistical validity of the results ($SP = 0.57$). A marginally significant difference was found between the less accurate every-trial condition ($M = 588.32$, $SD = 203.85$) and the every-10th-trial condition ($M = 387.19$, $SD = 139.78$; $p = .053$; $d = 1.17$). The effect size for this analysis ($d = 1.17$) also exceeds Cohen's (1998) convention for a large effect ($d = 0.80$) and the observed SP in our sample size supported the statistical validity of our results ($SP = .7$). There were no significant differences between the every-5th- and every-10th-trial conditions. Taken together, these results suggest that reduced feedback provided every 5th trial significantly enhances retention (learning) of the speech motor task when compared to a high-frequency feedback condition, and that providing high-frequency feedback following every trial is detrimental to retention (learning), as evidenced by significantly higher MAEs.

DISCUSSION

This study examined the effect of feedback frequency (after every trial, after every 5th trial, or after every 10th trial) on the learning of a speech motor task in neurologically healthy older adults. We hypothesized that optimal learning would be achieved with low-frequency feedback—that is, provided after every 5th and/or every 10th trial—analogous to the extant limb motor learning literature and a growing number of speech motor learning studies. When doing a slowed speech task, participants receiving low-frequency feedback (i.e., after every 5th trial) demonstrated significantly lower mean absolute error (MAE) (i.e., enhanced retention) compared to those receiving the high-frequency feedback (i.e., after every trial). Although participants in the every-10th-trial group performed similarly to those in the every-5th-trial group during retention testing (see Figure 2), there were no significant differences between the every-10th-trial and every-trial conditions. These findings are consistent with the extensive limb motor learning literature and the trend of a small number of speech motor learning studies that suggest provision of low-frequency feedback enhances retention of trained novel movements.

Methodological changes regarding practice amount in the current study may have contributed to the significant findings reported at the time of retention testing. Weir-Mayta and colleagues (2019), in a partial replication of Adams and Page's (2000) study, had participants practice the phrase, *"Buy Bobby a poppy"*, while attempting to match two target rates (2x and 3x slower than individual habitual rates) 30 times each for a total of 60 trials. Adams and Page had participants practice saying the same phrase 2x slower than a typical speaking rate (2400 milliseconds) 20 additional times for a total of 50 trials. When participants returned 2 days post-training for retention testing, those receiving low-frequency feedback (every 5th trial) had significantly lower MAEs than those receiving high-frequency feedback (every trial). When participants in the Weir-Mayta et al. (2019) study returned for retention testing 2 to 4 days post-training, measures of retention were not significant. One possible reason for the nonsignificant findings considered by the authors was the amount of practice, especially when considered in conjunction with the older population in Weir-Mayta et al.'s study. Although acquisition data suggested the speech task was sufficiently acquired, it is possible that the number of practice trials was insufficient to build an internal representation of the novel speech movement. Previous studies from both limb and speech have recognized the benefit of increased practice amount to enhance retention (see Kim et al., 2012; Maas et al., 2008, Schmidt & Lee, 2019; Wulf et al., 1998), especially for older adults (see Voelcker-Rehage, 2008 for a review). According to Pauwels, Chalavi, and Swinnen (2018), brain plasticity peaks in young age and then gradually decreases as we get older. Arguably because of this decreased plasticity, while new motor skills

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can be acquired at any age, the progress may be attenuated in older adults compared to young populations, hence the need for additional practice trials for older adults to achieve similar outcomes observed in their younger counterparts (Voelcker-Rehage, 2008). Utilizing a high number of practice trials provides the learner additional opportunities to establish connections between the various information associated with the movement (e.g., motor programs, GMPs, parameters), which helps to enhance the cohesion of recall and recognition schemas (Maas et al., 2008). Thus, it is important to provide the learner enough practice trials, along with optimal feedback frequency, to enhance learning (Kim et al., 2012; Wulf et al, 1998), which is a particularly important consideration when working with older adults, who need additional practice.

In alignment with previous studies, our findings suggest that a practice amount of 100 trials (50 trials per target rate), combined with a low-frequency feedback schedule following every 5th trial was optimal, leading to significantly enhanced post-training retention for our older participants (Adams & Page, 2000; Kim et al., 2012). In alignment with schema theory, we argue that increasing the practice amount resulted in our participants having more opportunities for the retrieval of stored motor programs. Across trials, relationships among various parameters associated with each movement, such as timing, are stabilized, thereby enhancing recall of the movement, and helping to automatize the activation of these programs and parameters for subsequent trials (Maas, et al., 2008; Schmidt et al., 2019; Coker, 2018). Thus, when learning a novel movement pattern, schema theory and the guidance hypothesis predict that an adequate number of practice trials, combined with the optimal frequency of feedback, is necessary and sufficient to optimize learning (Adams and Page, 2000; Kim et al., 2012; Wulf et al., 1998). Therefore, it appears that the number of practice trials, together with frequency of feedback, were sufficient and optimal for our older participants to encode and store a reliable internal model of the movement.

To expand on what was mentioned above, age of participants could be another reason Weir-Mayta and colleagues (2019) did not find the expected effect of feedback frequency on retention of the speech motor task. While benefits of low-frequency feedback have been demonstrated in limb motor learning (Winstein & Schmidt, 1990; Sparrow & Summers, 1992; Vander Linden et al., 1993; Wulf et al., 1998), the sample population for these experiments consisted of young participants. While there is no consensus in the limb motor learning literature regarding older adults and optimal feedback frequency (Ehsani et al., 2015), numerous studies have identified differences in how older adults learn new motor skills compared to young adults (Jamieson & Rogers, 2000; Nemeth & Janacsek, 2011; Romano et al., 2010; Shea et al., 2006; Voelcker-Rehage, 2008). In general, older adults can learn a new motor task, but they require a higher number of practice trials and perform with greater variability and less accuracy than younger adults. This variability in our older participants can be seen in Figure 2, evidenced by a large spread in error bars representing standard error of the mean during acquisition. For younger adults, clear distinctions between those receiving high-frequency feedback (e.g., every trial) versus those receiving low-frequency feedback (e.g., every 5th trial) can be observed early during the practice session, with those receiving low-frequency feedback presenting with higher error scores; over time, however, error scores decrease, and their performance becomes similar to those receiving high-frequency feedback. The reason for this relates to the guidance hypothesis (see Salmoni et al., 1984; Schmidt, 1991; Winstein & Schmidt, 1990) and can be seen, for example, during the acquisition phase of Adams and Page's (2000) study. For the older adults in the present study, however, this expected pattern is not clearly seen, especially for participants in the every-trial and every-10th-trial groups. However, for those receiving feedback following every 5th trial, this expected pattern was more evident (see Figure 2). In fact, considering the statistics provided and data visualization in Figure 2, participants receiving feedback following every 5th trial demonstrated better performance overall for both acquisition and retention than those in the other two feedback conditions. While the every-10th-trial group's performance during retention testing was similar to that of the every-5th-trial group, there was no significant difference found when compared to the every-trial group. Thus, in line with expectations provided by the guidance hypothesis, feedback provided every 5th trial was more effective in both acquisition and retention of the speech motor task.

In a recent study by Bindra et al. (2021), the researchers explain that normal aging can selectively decrease the temporal stability of short-term implicit motor learning. Thus, the greater retention during lower frequency feedback in our study can be viewed through the lens of separate learning mechanisms that operate on different timescales (McDougle, Bond & Taylor, 2015). Originally proposed by Smith, Ghazizadeh and Shadmehr (2006), the motor adaptation processes and learning can be subdivided into at least two distinct neural systems with both a slow and a fast component. While the fast component is more subject to passive decay, the slow learning component is much more temporally stable and resilient to the passage of time. Moreover, the fast explicit learning process (as induced by high-frequency feedback) is heavily reliant on wide attentional and executive networks (Taylor & Ivry, 2014). The efficacy of such networks and the performance of their respective cognitive domains are commonly decreased or impaired in the aging population The differences in overall cognitive performance within the aging population can also significantly alter the effectiveness of online and offline learning of motor tasks (Yan, Abernethy, & Li, 2010). Subjects would require different time until they reach asymptote, and such changes can serve as a potential explanation for the great variability seen in our acquisition trials (Figure 2). On the other hand, the lower variability rate at the retention stage of the study is reflective of already consolidated and temporally stable patterns. Although our groups were similar in years of education (as a measure of cognitive reserve), a future study can utilize more concrete global and domain-specific cognitive tests (e.g., Delis-Kaplan Executive Function System) that would allow cognition-based corrections during the comparisons.

In sum, the results of this study are consistent with findings seen in the limb motor learning literature and the growing body of speech motor learning studies. Increased practice amount, combined with a low-frequency feedback schedule, enhances the learning of the speech motor task in our healthy older participants. The theoretical underpinnings driving these results are best explained using the guidance hypothesis, which suggest that there can be a detrimental effect of high-frequency feedback, wherein the learner becomes dependent on its guiding properties (Winstein & Schmidt, 1990). Providing feedback less often allows the learner to problem solve and develop their own internal model of the motor task at hand. When working with older individuals, it is also important to be mindful that, although they can learn novel movements, more practice trials may be needed for accuracy and retention levels to approximate those seen in younger adults (Voelcker-Rehage, 2008). Focused interventions that keep in mind the slow component of the canonical learning process may further improve the outcomes in older individuals.

CLINICAL IMPLICATIONS

The PML have been a driving force in the training and retraining of limb movements for years. Although their application to speech motor learning is still unclear, especially for those with motor speech disorders, clinicians should be mindful of the emerging evidence. Results from the current study suggest that, for those without nervous system pathology, increased practice amount and randomized practice, combined with a low-frequency feedback schedule, can enhance retention of novel speech motor movements. These results are consistent with findings from Adams and Page (2000) and Kim et al. (2012) in healthy adult participants, as well as with findings from Adams, Page, and Jog (2002), who investigated individuals with Parkinson's disease. While clinicians should recognize the potential development in ongoing praxis, there is still a need for more research before specific therapy protocols can be put into place. Encouraging results have been seen utilizing a high practice amount, randomized practice schedule, and low-frequency feedback for individuals with Parkinson's disease (Adams, Page, and Jog, 2002) as well as the use of motor learning principles in Lee Silverman Voice Treatment (LSVT-Loud) treatment. However, research on intervention approaches for individuals with acquired Apraxia of Speech (AOS) remains unclear (Bislick et al., 2013; Wambaugh, 2002; Wambaugh, Duffy, McNeil, Robin, & Rogers, 2006a, 2006b). Findings from the current investigation highlight the potential benefits of the PMLs to speech and the need for additional research in both healthy and impaired motor speech systems.

LIMITATIONS OF THIS STUDY

Although the current findings suggest that practice amount is sufficient for the speech motor task selected, it remains unclear if the same number of practice trials would be sufficient for other speech tasks and/or for clinical populations. More complex motor speech tasks may require greater practice amount while others may require less, with clinical populations possibly needing an even greater amount of practice trials for the same task(s) (Dunham & Mueller, 1993; Lowe & Buckwald, 2017; Weir-Mayta et al., 2019). Second, the age range was quite large, and the mean age was young for what is generally considered “older adults”. Although the age range reflects the age typically associated with some clinical populations (e.g., Parkinson’s disease) typically seen on speech therapy caseloads, future studies should include additional older adults (i.e., 65+). Third, a control group of participants who did not receive any feedback during the acquisition phase would help to clarify if the gains observed in the every-5th- and every-10th-trial conditions at the time of retention testing can be attributed to the selection of optimal feedback frequency or simply to practice effects. Finally, it is important to recognize the role that sleep plays in memory consolidation and encoding (Humiston & Wamsley, 2018), which is something we did not control for in our study. Future studies should explore differences in task complexity and practice amounts to identify a clearer understanding for a variety of speech movements.

Although our power analysis gave us confidence that 10 participants per group was sufficient and we achieved a significant result at the time of retention testing, given the variability seen in our older adults, future studies may want to consider adding additional participants to gain a clearer picture of acquisition. It may also prove fruitful to explore other principles of practice and feedback conditions to examine more closely how older adults acquire speech motor tasks.

The current study also did not examine generalization or long-term retention (e.g., 1 to 6 months post-training), making it unknown how well the trained speech task will generalize to untrained movements and the maintenance of long-term learning. Future studies should consider adding a generalization component and should conduct retention testing at various stages post-training (e.g., immediate, days, weeks, months). Doing so in the current study may have yielded results differentiating the every-5th- and every-10th-trial groups more clearly.

Finally, the current study focused on one PML, feedback frequency, on the learning of a speech motor task presented via a random practice schedule. Thus, it remains unclear how best to combine PMLs—for example, feedback delay with random practice and/or various levels of practice amount—to enhance learning outcomes. Future studies should extend investigations to other feedback schedules (e.g., faded feedback) and to the possible interaction effects among PMLs (c.f., Kim et al., 2012; Maas et al., 2008). Finally, inclusion of healthy adults across the lifespan would aid in our understanding of how speech motor learning changes as people age.

CONCLUSION

This study has contributed to the growing body of literature that shows that increased practice amount, combined with a low-frequency feedback schedule, is beneficial when training novel speech movements. While current speech motor learning literature has focused primarily on young healthy adults, results of the current study suggest that older adults can learn speech motor task as well when provided with the optimal combination of high practice amount and low-frequency feedback. While findings from the current study are encouraging, more evidence is needed—in both healthy older adults and those with neurological impairments—before therapeutic protocols utilizing motor learning principles can be developed and put into practice.

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COMPETING INTERESTS

The authors have no competing interests to declare.

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