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Investigation of Feedback Schedules on Speech Motor Learning in Older Adults

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ABSTRACT

Background: 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. **Aims:** The purpose of this study was to examine one PML, feedback frequency, and its effect on retention and generalization of a novel speech and comparable tracing task. **Methods:** Sixty older adults completed a speech motor learning task requiring the production of a novel phrase at speaking rates 2 times and 3 times slower than habitual rate. Participants also completed a limb motor learning task requiring the tracing of a sine wave 2x and 3x slower than habitual rate. Participants were randomly assigned to receive feedback every trial, every 5th trial, or every 10th trial. Mean absolute error was measured to examine immediate generalization, delayed generalization, and 2-day retention. **Findings:** Results suggested that feedback frequency did not have an effect on the retention and generalization of the speech or manual task, supporting the small but growing literature highlighting the constraints of generalizing the PML to other modalities and populations.

Keywords: motor learning, feedback, generalization, speech, limb

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There is growing interest in the application of motor learning principles to the field of speech-language pathology (Maas, Robin, Austermann Hula, Freedman, Wulf, Ballard, & Schmidt, 2008). The principles of motor learning (PML) are a set of processes associated with practice or experience, leading to relatively permanent changes in the capability for movement (Schmidt & Lee, 2014). These principles can be divided into variables related to the *structure of practice* and the *nature of feedback*. Principles relating to the structure of practice pertain to how a training session is implemented, taking into account issues such as blocked versus random presentation of training targets and mass versus distributed practice schedules. Principles relating to the nature of feedback, on the other hand, are concerned with the type and frequency of feedback regarding movement outcomes, provided during instruction. PML have considerable implications for an individual's ability to learn, recall, and maintain skilled movements (Schmidt & Lee, 2014). Thus, identifying optimal practice and feedback conditions for the training or re-training of speech is a valuable endeavor that will shape how novel motor skills are taught across a broad spectrum of research and clinical settings.

Numerous investigations of young, healthy adults have led to robust evidence that the use of motor learning principles leads to improved retention of trained upper limb movements (e.g., Park & Shea, 2003, 2005; Winstein & Schmidt, 1990; Wulf & Schmidt, 1997). Yet relatively few studies have examined the influence of the PML when training older learners and even fewer have investigated the modality of speech. The aim of the current study is to examine the influence of one PML, feedback frequency, on the ability of older, healthy adults to learn a novel speech movement and a comparable limb movement.

As the wealth of motor learning research has been founded on young adults, the effectiveness of the PML in older adults remains uncertain. Some investigators purport that older learners perform comparably to their younger counterparts (Fraser, Li, and Penhune, 2009; Lin, Wu, Udompholkul, & Knowlton, 2010). However, age-related differences in motor learning are frequently reported (Chaput & Proteau, 1996; Jamieson & Rogers, 2000; Swanson & Lee, 1992; Voelcker-Rehage, 2008; Wishart, Lee, Cunningham, & Murdoch, 2002). For example, the rate of acquisition and amount of learning retained can be less than that found in younger adults. Specifically, older learners may have difficulty acquiring motor skills of increased sequential complexity (Romano, Howard, J., Howard, D., 2010; Shea, Park, Braden, 2006), show deficits in motor sequence consolidation (Nemeth and Janacsek, 2011; Shea et al., 2006), and/or have degraded performance accuracy when provided with explicit information about a long, repeating movement sequence (Spencer et al., 2007; Voelcker-Rehage, 2008). Processing of explicit movement information by older adults may also result in a ceiling effect of cognitive processing capacity (Frensch and Runger, 2003; Frensch and Miner, 1994). Thus, observed differences in motor skill acquisition may be due, at least in part, to age-related changes in cognitive functioning (Carnahan, Vandervoort, & Swanson, 1996; Salthouse, 1996; Howard and Howard, 2013; Howard, Howard, Dennis, Yankovich, and Vaidya, 2004; Rieckmann and Bäckman, 2009; Voelcker-Rehage, 2008) and the accompanying structural or dopaminergic changes associated with aging (Rieckmann and Bäckman, 2009; Rieckmann, 2010). It is therefore imperative to extend investigations of the PML to older learners.

Unknown at this time is whether PML will seamlessly transfer from limb motor learning to speech motor learning. Speech articulation is a highly complex motor skill, performed at an exceptionally fast rate, without visual feedback from the structures involved. Unlike limb function, many speech movements do not involve the movement of a joint, but require symmetric and synchronous movements of bilaterally innervated structures. Despite these differences, it is possible that limb and speech motor control share enough similarities in the requirements for movement planning, movement trajectory, timing, coordination, sequencing, and biomechanics (Grimme, Fuchs, Perrier, & Schoner, 2011) that the PML may be applicable to and facilitate motor learning in speech as well.

In the limb motor learning literature, there is strong evidence that a relatively low frequency feedback schedule enhances learning (Winstein & Schmidt, 1990; Sparrow & Summers, 1992; Vander Linden, Cauraugh, Greene, 1993; Weeks & Kordus, 1998; Wulf, Shea, and Matschiner, 1998). While the majority of these studies are based on younger adults, several studies have suggested that older adults similarly benefit from a reduced feedback schedule (Carnahan et al., 1996, Guadagnoli, Leis, Van Gemmert, & Stelmach, 2002), despite some age-based differences (e.g., increased spatial error in older adults; Carnahan et al., 1996). According to the guidance hypothesis (Salmoni, Schmidt, & Walter, 1984; Schmidt, 1991), high frequency feedback quickly guides the learner to accurate performance during acquisition of the skill, but degrades retention of that skill. In contrast, low feedback frequency often slows acquisition but enhances retention (Winstein & Schmidt, 1990). If feedback is provided too frequently, the learner may become reliant on the external guidance and fail to process proprioceptive information necessary for permanent encoding of the motion. When feedback is provided less frequently, the learner has an opportunity to detect and correct errors independently, thus facilitating the use of effective strategies that aid in accurate completion and recall of the skilled movement (Schmidt & Lee, 2014; Swinnen, Schmidt, Nicholson, and Shapiro, 1990; Winstein and Schmidt, 1990; Gable, Shea, and Wright, 1991; Young and Schmidt, 1992; Weeks and Sherwood, 1994; Yao, Fischman, and Wang, 1994). Despite converging evidence in support of decreased feedback frequency, not all limb motor learning studies have been consistent with this view and the premise of the guidance hypothesis. Several studies have failed to show a detrimental impact of 100% feedback frequency (Lai & Shea, 1998; Wulf et al.,1998; Wulf & Shea, 2004), leading Wulf, Chiviacowsky, Schiller, and Gentilini Ávila (2010) to suggest that the relative benefits of feedback frequency may be linked to the specific training conditions and task complexity.

To determine if reduced feedback frequency benefits speech motor learning, several studies have examined the effect of feedback frequency on the ability to learn novel speech movements. All studies were conducted with healthy, young adults. Thus far, the majority of findings support the premise that reduced feedback frequency benefits participants similarly to limb motor learning studies. Particularly germane to the present study is the investigation of Adams and Page (2000), which compared the effects of feedback provided every trial to summary feedback provided every fifth trial on the learning of a novel speech task in a group of 20 young female participants. The speech task required participants to produce the phrase, ‘Buy Bobby a poppy’ with a duration of 2400 ms, approximately two times slower than a typical rate of speech. Visual feedback was provided to both feedback groups using absolute error as the outcome measure. Results suggested that less frequent feedback improved performance on retention testing two days post training. Speech motor learning benefits from reduced feedback also were reported by Steinhauer and Grayhack (2000) and Kim, LaPointe, and Stierwalt (2012). However, inconclusive results were reported by Lowe and Buchwald (2017) who examined the influence of feedback frequency in young adults during a nonword production task. Participants received feedback according to a randomly assigned schedule (100%, 50%, 20%, or 0%). Improvements were similar at both short-term and long-term retention testing for all participants, with no significant differences between feedback conditions as measured by nonword accuracy. The authors speculated that the number of practice trials may have been too few, not allowing participants to fully encode and store the newly practiced motor skill.

Thus, there is robust evidence to support reduced feedback frequency when training a novel limb motor task to young, healthy adults. However, transference of this principle to older adults, or to the training of novel speech tasks is currently unknown. It is important to understand the effect of feedback frequency because of its potential to degrade learning. As little is known about optimal feedback schedules, and many speech treatment protocols do not explicitly state instructions for feedback delivery, high frequency feedback is often provided (Ballard, Granier, & Robin, 2000; Lowe & Buchwald, 2017). Thus, it is imperative to understand whether the provision of lower frequency feedback, shown to be beneficial in younger adults during limb movement tasks, will extend to older adults and the speech modality.

The present study was designed as a partial replication and extension of Adams and Page (2000) to examine the effect of feedback schedule (every trial, summary every 5th trial, summary every 10th trial) on the ability of older adults to learn a novel speech task and a comparable limb task. Maintenance of learning (2-4 days post training) and generalization to novel speech and limb movements were also measured. It was hypothesized that optimal learning for speech tasks would be achieved with low levels of feedback analogous to the majority of extant limb and speech motor learning studies in young adults.

Methods

Participants

Participants were consented before study participation in accordance with the Institutional Review Board. Sixty adults completed the study: 19 males and 41 females, with a mean age of 61.7 years (range 44-84 years), and a mean education of 16.9 years (range of 10-26 years; see Table 1). All participants were native speakers of American English, had adequate visual acuity, adequate hearing thresholds $\leq$ 50 dB at 500, 1000, and 2000 Hz, and typical speech, language, and cognitive developmental history. All participants successfully passed a depression, language, and cognitive screening.

Procedures

The experiment consisted of two phases. Phase I involved screening, instruction, training, and measurement of immediate generalization of both the speech and manual tasks. Phase II occurred two to four days post training and involved measurement of retention and generalization for the speech and manual tasks.

Phase I. Participants who met all selection and screening criteria were randomly assigned to one of three groups (feedback every trial, every 5th trial, every 10th trial). Participants were seated in front of a computer monitor; the examiner sat beside the participant at a computer running MATLAB. During the *instructional phase*, the participants were oriented to the visual feedback display, and habitual rates of the novel speech task (speaking at a slower than typical duration) and manual task (tracing at a slower than typical duration) were measured following two demonstration trials performed by the experimenter. Order of speech and manual task presentation was counterbalanced.

To obtain the participant’s habitual rate for the speech task, each speaker was directed to say the target phrase, *Buy Bobby a poppy* 10 times at their normal speaking rate. Results were digitally recorded, and the duration of each production was determined with software custom-written in MATLAB. Results were 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 participant was 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 on one breath, elongating the vowels, as modeled by the experimenter. A comparable procedure was used to determine habitual rate for the manual task, where participants were asked to trace a horizontal sine wave from beginning to end using a wireless computer mouse. Participants were able to see the cursor movement superimposed over the target pattern.

Upon completion of the instructional phase, participants began the *acquisition phase* during which they completed 30 trials attempting a 2x slower target duration and 30 trials attempting a 3x slower target duration for a total of 60 acquisition trials. Speech and manual tasks were presented in a counterbalanced order. Target durations were randomly presented by the computer program. To inform the participant of the target rate, the labels “2x” or “3x” were displayed on the monitor before the initiation of a trial and remained throughout trial execution. The MATLAB program allowed for a maximum of 30 seconds to complete the task before timing out. No incidents of timing out occurred during the experiment. 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). Participants were allowed to view the feedback display for as long as they needed (typically < 5 seconds). One group of participants received such feedback after every trial, one group received summary feedback after every 5th trial (i.e., all of the preceding 5 targets were provided simultaneously on the display), and one group received summary feedback after every 10th trial. Following the acquisition trials, the participants completed a *generalization task* where their accuracy at matching a specific target rate was measured for the production of a similar phrase, “Dye Didi a tutu” for the speech task. This phrase was selected because it has been suggested that speech motor learning transfers across the effector parameter (i.e., labial vs. alveolar; Maas et al., 2008). The generalization task for the manual protocol was to trace the sine wave presented vertically (instead of horizontally) from top to bottom. Participants were asked to complete 20 trials (10 trials at the 2x slower rate and 10 trials at the 3x slower rate) without feedback about performance accuracy, for both the speech and manual tasks.

Phase II. Participants returned 2-4 days post training for retention testing. Subjects completed 40 trials for both the speech and manual tasks (20 trials with the 2x slower target and 20 trials with the 3x slower target) and 20 trials of the generalization tasks (10 trials at the 2x slower target and 10 trials at the 3x slower target) with no feedback provided. See table 2 for a summary of the experimental paradigm.

Instrumentation. To present and analyze parameters of the speech and manual tasks, custom software written in MATLAB (MATLAB 7 with the Data Acquisition Toolbox, MathWorks, 2007) programming environment was employed. It consisted of three graphical user interfaces: a single control window for the setting of parameters by the experimenter, and two separate “subject interaction” windows for the speech and manual tasks. 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 one of the two interaction panels (speech or manual task) was presented, 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 MicroMic C520/C520L head mounted microphone was connected to an audio interface, M-Audio Fast Track. 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 MATLAB program. Microphone gain setting was consistent across participants.

Data Analyses.

A power analysis (Cohen, 1988, 1992) was performed using GPower 3.1.9.2 software (Faul, Erdfelder, Lang, & Buchner, 2007; Faul et al., 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, Mintz, Noda, Tinklenberg, & Yesavage, 2006). Traditional criteria were assumed ($p < .05$; two tailed; power = 80%; and Cohen’s effect size guidelines, e.g., $d = 0.2$, 0.5, and 0.8 for small, medium, and large effects, respectively). Borrowing from Adams and Page, where M1 (feedback 1) = .593, M2 (feedback 5) = .281, with an average SD = .123, we calculated that past research found a very large effect size of Cohen's $d = 2.53$. Applying that effect size to the present study, we found that the chance of detecting a similar mean difference with N = 20 per cell was >99.9%.

Mean Absolute Error (MAE) was the dependent variable used to measure deviation from the targeted duration. ANOVAs revealed no significant main effects or interactions involving target rate conditions across each of the three measurement periods (immediate generalization , delayed generalization, 2-day retention), thus the 2x and 3x rates were collapsed for both speech and manual tasks. Six one-way ANOVAs were conducted to examine the impact of feedback condition on immediate generalization, delayed generalization, and 2-day retention for the speech and manual tasks.

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

Feedback Group	Every Trial	Summary 5	Summary 10
Total Participants	20	20	20
Gender	13F 6M	17F 3M	10F 10M
Age	62.3 (10.47)	59.9 (10.51)	62.9 (6.92)
Education (years)	16.5 (2.08)	16.9 (2.99)	16.9 (2.25)
Habitual Speaking Rate (ms)	1512 (262.01)	1569 (271.26)	1502 (342.35)
Habitual Tracing Rate (ms)	3867 (1463.81)	4526 (1994.80)	4187 (2068.28)

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

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

	Phase I				**Phase II**	
	Habitual Rate	Instructional Phase	Acquisition Task	Immediate Generalization	Retention of Trained Task	Retention of Generalization Task
Speech Task	“ Buy Bobby a Poppy”			“Dye Didi a Tutu”	“ Buy Bobby a Poppy”	“Dye Didi a Tutu”
	10 trials	4 trials total: 2 at 2x slower 2 at 3x slower	60 trials total: 30 at 2x slower 30 at 3x slower	20 trials total: 10 at 2x slower 10 at 3x slower	40 trials total: 20 at 2x slower 20 at 3x slower	40 trials total: 20 at 2x slower 20 at 3x slower
Manual Task	Horizontal Sine Wave			Vertical Sine Wave	Horizontal Sine Wave	Vertical Sine Wave
	10 trials	4 trials total: 2 at 2x slower 2 at 3x slower	60 trials total: 30 at 2x slower 30 at 3x slower	20 trials total: 10 at 2x slower 10 at 3x slower	20 trials total: 10 at 2x slower 10 at 3x slower	20 trials total: 10 at 2x slower 10 at 3x slower

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

Feedback Condition	First Block MAE (SD)	Last Block MAE (SD)	*t*	*p*
Speech				
1	432.01 (1328.89)	296.90 (609.38)	3.477	.003
5	520.95 (1418.34)	289.21 (1092.60)	3.297	.004
10	622.52 (2388.15)	415.84 (667.46)	2.651	.016
Manual				
1	1602.74 (130.98)	1045.65 (118.70)	2.156	.044
5	1989.25 (321.51)	1591.09 (120.39)	1.130	.272
10	2633.40 (326.54)	1121.76 (226.52)	2.883	.010

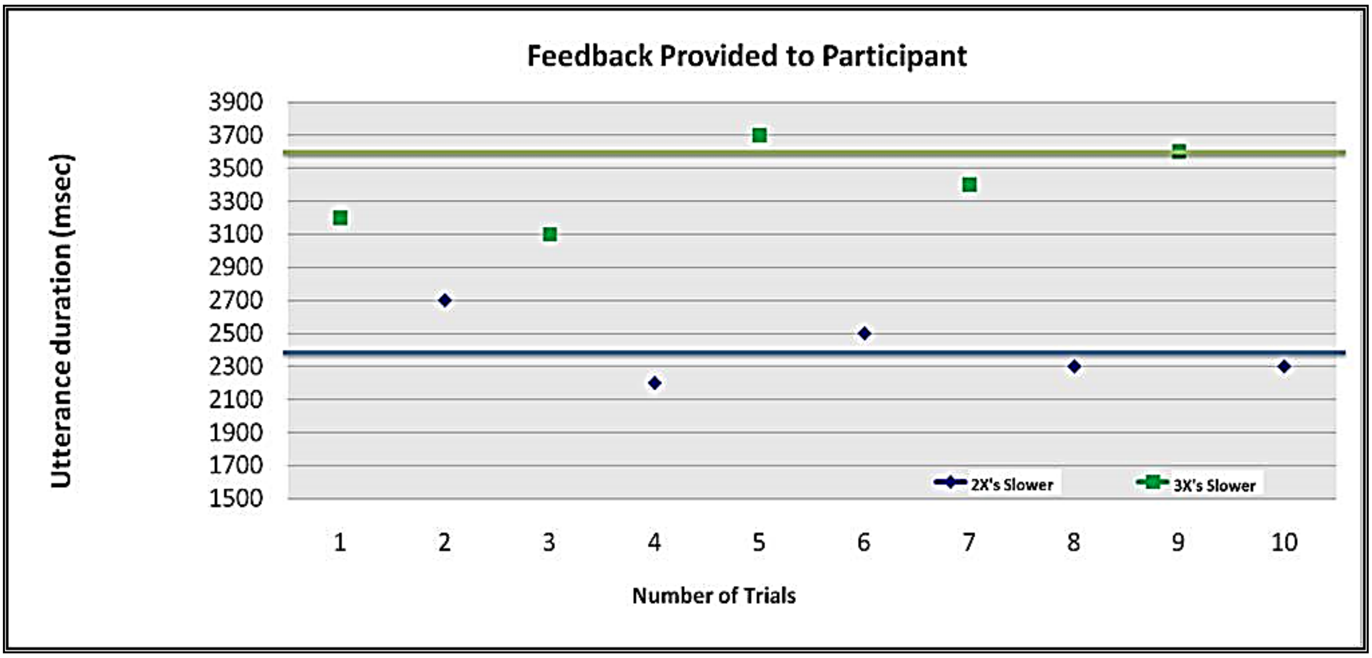

Figure 1. Example of a visual feedback graph for the first 10 trials, provided to participants in the feedback every trial condition. Data represent recorded duration and distance (error) from the target duration, colored coded blue for “2x” slower and green for “3x” slower. To limit the usable amount of feedback provided, utterance duration rates in milliseconds along the y-axis were not visible to participants.

Results

Reliability

To test reliability of speech duration measurements calculated by the MATLAB software, a blind comparison was made between MATLAB calculations and manual calculations performed in Adobe Audition. Random durations from 33% (20/60) of the total acquisition speech trials per individual were calculated. Results showed a strong correlation, r (240) = .972, $p < .001$, suggesting that the data captured in MATLAB were accurate.

Acquisition

To verify that the acquisition trials were effective and that participants learned the tasks, within-subject *t*-tests were conducted comparing the MAE for the first five trials at the combined 2x and 3x target rates with the last five trials of the combined 2x and 3x target rate, per feedback group. Results indicate that MAE decreased significantly in all but one condition (manual every 5th trial) suggesting an overall pattern of acquisition (see Table 3).

Retention and Generalization

Speech Task. Results of a one-way ANOVA were not significant for effect of feedback condition on MAE during retention [*F*(2,57) = 1.079, *p* = .347], immediate generalization [*F*(2,57) = 0.40, *p* = .960], or delayed generalization [*F*(2,57) = 0.164, *p* = .85]. See Figure 2.

Manual Task. Results of a one-way ANOVA revealed no significant effect of feedback condition on MAE for retention [*F*(2,57) = 1.146, *p* = .325], immediate generalization [*F*(2,57) = 2.063, *p* = .137], or delayed generalization [*F*(2,57) = .904, *p* = .411]. See Figure 3.

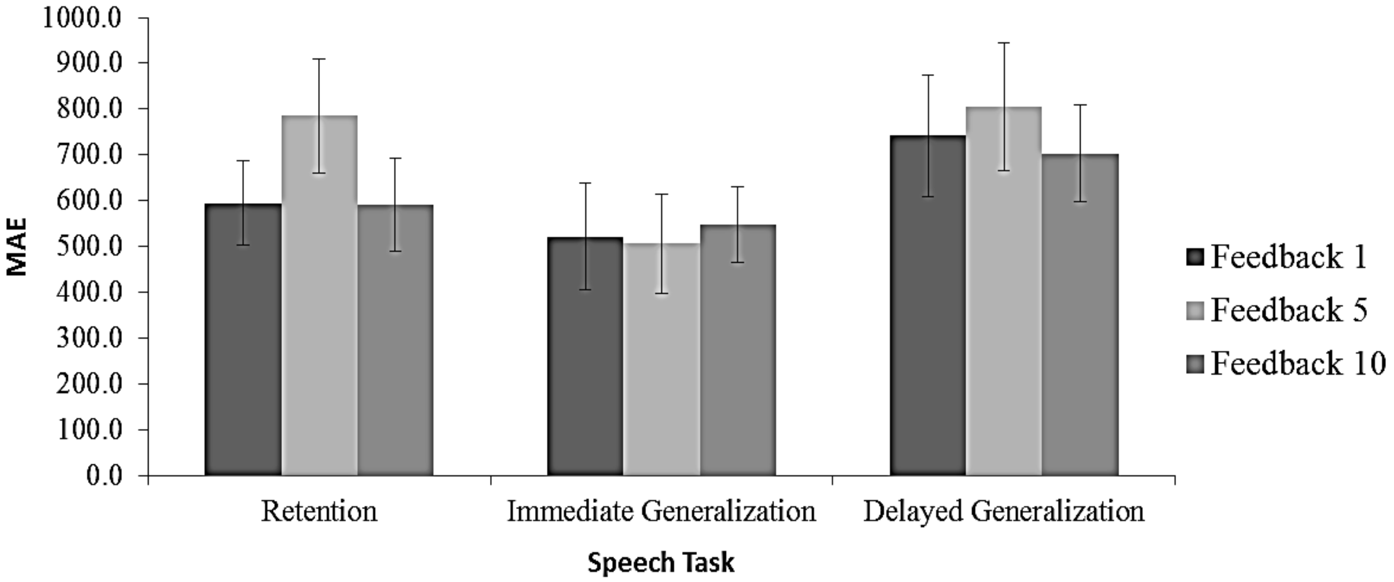

Figure 2. Mean absolute error and standard deviations for the Speech task across retention and generalization measurements. Error bars represent standard error of the mean.

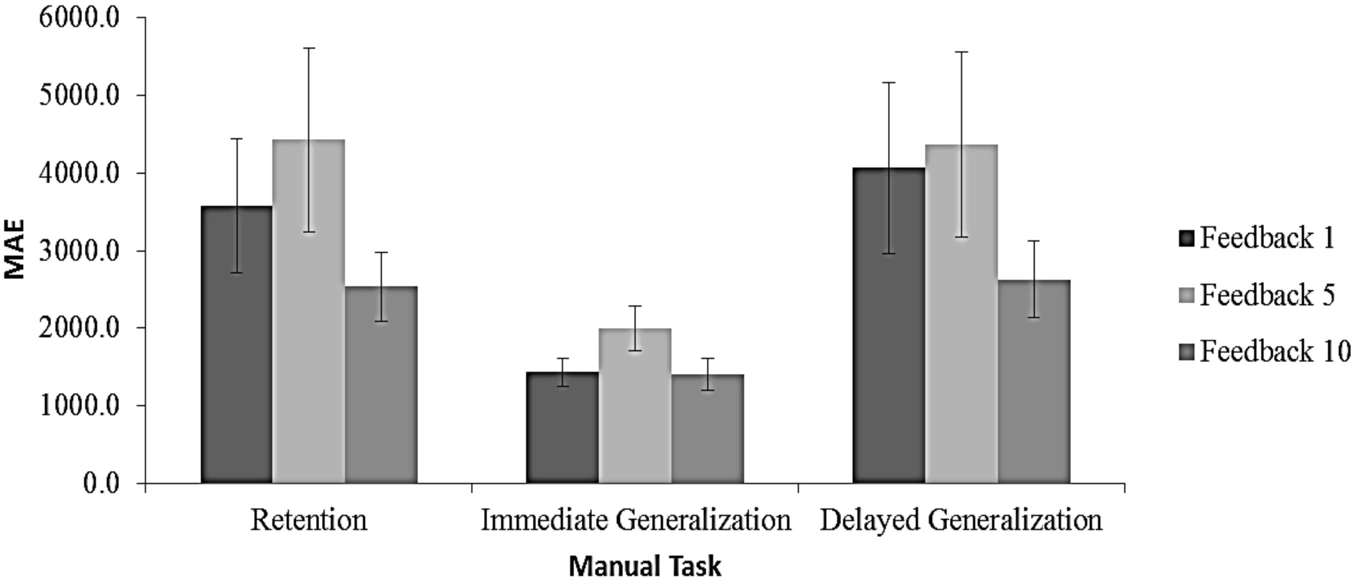

Figure 3. Mean absolute error and standard deviations for the Manual task across retention and generalization measurements. Error bars represent standard error of the mean.

Discussion

The purpose of this study was to examine the effect of feedback frequency manipulations on the learning of a novel speech and manual task in older adults. Based on the extensive limb motor learning literature, and the trend of a small number of speech motor learning studies, we predicted that performance on a rate modification task would be enhanced by a reduced feedback schedule. Sixty participants were randomly assigned to one of three feedback frequency groups and trained to produce a target utterance or a manual tracing at a rate that was 2x or 3x slower than their habitual rate. Participants demonstrated a reduction in error during the training, regardless of feedback group, suggesting they understood the task and were adjusting their behavior to approximate the slower rate. However, measures of retention and generalization were not significantly affected by feedback frequency for the speech or manual task.

As this study was a partial replication of Adams and Page (2000), it is fruitful to first consider methodological differences that could have contributed to the disparate outcomes. In the Adams and Page study, a set speech target rate was implemented (i.e., 2400 ms or approximately 2x slower than usual), whereas the current design calculated target rates based on each speaker's habitual speech rate. Between-speaker differences in habitual speech rates are common (Jacewicz and Fox, 2010) and were evidenced in the current study. Thus, the individualized targets truly reflected the 2x and 3x slower rates of speech, and were perhaps more sensitive to individual aspects of rate modification. Additionally, the method for providing feedback differed between the two studies. Adams and Page (2000) manually calculated feedback, thus, the extra time required to perform these calculations introduced a delay component not present in the current investigation. Feedback delay is a PML shown to enhance limb motor learning in healthy, young adults (Schmidt & Wulf, 1997; Vander Linden et al., 1993; Schmidt & Lee, 2014; Swinnen et al., 1990). The combination of feedback schedule and feedback delay may have resulted in a cumulative effect that altered learning outcomes. To control for this in the present study, results were calculated and displayed instantaneously, which allowed for isolation of the principle of interest, feedback frequency.

Our finding that feedback frequency did not influence rate modification for the speech or limb motor learning task could be related to several factors. The first consideration relates to age. The benefits of a reduced feedback schedule on limb motor learning have been robustly demonstrated (Winstein & Schmidt, 1990; Sparrow & Summers, 1992; Vander Linden et al., 1993; Wulf et al., 1998). However, these experiments have largely been conducted on younger adults (and children; Weeks & Kordus, 1998). At present, there is no consensus in the literature regarding limb motor learning expectations for older adults (Ehsanni, Abdollahi, Bandpei, Zahiri, and Jaberzadeh, 2015), though numerous studies have highlighted a reduction in motor learning capacities in older participants (Jamieson & Rogers, 2000; Romano et al., 2010; Shea et al., 2006; Nemeth and Janacsek, 2011; Shea et al., 2006; Voelcker-Rehage, 2008). Additionally, the small handful of speech motor learning studies related to feedback frequency, the majority of which endorse reduced feedback schedules, have all employed young adults. Thus, the impact of feedback frequency on the speech motor learning of older adults remains uncertain. The second consideration relates to practice amount. Although acquisition data suggest the speech and limb motor tasks were sufficiently acquired (see Table 3), it is possible the number of practice trials was insufficient to build a stable internal representation of the novel movements. Studies investigating speech and limb motor learning have demonstrated the benefit of large amounts of practice to enhance retention of newly acquired motor skills (Kim et al., 2012;

Maas et al., 2008; Wulf et al., 1998). Providing a high number of trials allows more opportunity 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 and Lee, 2014). Thus, when learning a novel, complex motor skill, it is necessary to present an adequate number of practice trials along with the optimal frequency of feedback to optimize learning (Kim et al., 2012; Wulf et al., 1998). In the current study, our participants had 30 opportunities to practice the phrase per target rate, for a total of 60 practice trials. This number is on the lower end of most previous studies of feedback frequency which required participants to practice a target 40-100 times (Adams & Page, 2000; Kim et al., 2012; Steinhauer & Grayhack, 2000). The exception is the study by Lowe and Buchwald (2017) that only employed 10 practice trials; these authors also found no effect of feedback frequency on speech motor learning (i.e., nonword production). Thus, it is possible that the number of practice trials in the current experiment was insufficient and, subsequently, the participants failed to encode and store a reliable internal representation of the movement.

A high number of practice trials is particularly important for older learners. It is well established in the broader gerontology literature that age-based learning differences exists, and must be considered when training older individuals (King, Fogel, Albouy, Doyon, 2013; Rodrique, Kennedy, Raz, 2005; Seidler, Bernard, Burutolu, Fling, Gordon, Gwin, 2010; Voelcker-Rehage, 2008). This notion is also reflected in the speech motor learning literature. That is, although both younger and older adults will show improvement with practice, younger adults produce faster and more consistent movements and retain the task better than older adults (Schulz, Stein, & Micallef, 2001; Sadagopan & Smith, 2013). Additionally, evidence suggests that older adults require more practice trials to create a stable, reliable motor pattern compared to their younger counterparts (Voelcker-Rehage, 2008).

The third consideration relates to variability of performance. As a whole, the participants understood the task, showed improvement during the acquisition phase, and were able to process the computerized feedback of the discrepancy between attempted and targeted productions. However, there was considerable interparticipant variability in the response patterns within groups, which may have obscured differences between the feedback groups. While it may be ideal for subsequent studies to investigate feedback schedules using a within-participant paradigm, this approach is very time consuming and logistically difficult (e.g., Austermann Hula et al., 2008) as it is hard to control for possible generalization effects (Lowe & Buchwald, 2017).

In sum, the lack of a feedback frequency effect has been attributed to numerous issues, including insufficient number of practice trials (Dunham & Mueller, 1993; Lowe & Buckwald 2017), as well as task specificity matters (Sparrow, 1995), and limited time between acquisition trials and retention testing (Wishart & Lee, 1997). Thus, the ideal feedback schedule remains unclear and is likely shaped by interaction with other PML, such as feedback delay and the number of practice trials, as well as influential factors such as the complexity of the task and the age of the learners.

In the broader context, the findings of this study align with the small but growing literature highlighting the constraints of generalizing the PML to other modalities and populations. While there is evidence to suggest that principles guiding limb motor learning should translate to speech motor learning (Adams & Page, 2000; Kim et al., 2012; Maas et al., 2008; Steinhauer & Grayhack, 2000), this assumption remains tenuous and requires continued, systematic research across the PML and speech behaviors. Despite considerable convergence between theories of speech and limb motor learning, such as the need to process movement trajectories for goal-directed movements, there are also critical differences, such as the level of inter-gestural coordination, biomechanical constraints, and the high velocity of speech movements (Grimme et al., 2011). Moreover, speech motor learning has been shown to be highly contextually specific, failing to transfer even to utterances that involve similar movements (Tremblay, Houle, and Ostry, 2008). These differences may be contributing to the negative/mixed findings recently reported in studies of the PML in healthy speakers (Kaipa, 2016; Lowe & Buchwald, 2017), including the present study, as well as speakers with speech impairment (Adams, Page, and Jog, 2002; Austermann-Hula, Maas, Ballard, and Schmidt, 2008; Bislick, Weir, and Spencer, 2013; Katz, McNeil, and Garst, 2010; Maas, Butalla, and Farinella, 2012; Wambaugh, Nessler, Wright, Mauszycki, and DeLong, 2016; Wambaugh, Nessler, Wright, and Mauszycki, 2014; Wambaugh, Nessler, Cameron, and Mauszycki, 2013) and suggest judicious application of PML, such as feedback frequency, to speech motor learning.

Limitations and Conclusions

Results of this study highlight a number of methodological considerations that need to be taken into account when investigating feedback frequency. First, while our sample size of 60 was the largest among the speech motor learning studies, more participants per feedback condition may have helped to offset the considerable variability associated with the speech and limb motor learning tasks. Second, the inclusion of adults across the lifespan would have allowed us to offer more definitive conclusions regarding the effects of aging on speech motor learning. Finally, retention and generalization were measured 2-4 days after training, which may not be sufficient to examine the long-term effect of motor learning.

Future studies should extend investigations to other feedback schedules (e.g., faded feedback) and to the possible interaction effects among PML (i.e., Kim et al., 2012; Maas et al., 2008). Intensity of practice should be increased as converging evidence suggests that a greater number of trials can stabilize the motor pattern and result in improved motor learning (e.g., Kim et al., 2012). It may also be fruitful to examine characteristics of speakers who respond better to motor learning tasks and treatments versus those who do not; individual factors may shed light on the variability in motor learning task/treatment outcomes (Preston, Leece, & Maas, 2017). Finally, benefits of reduced feedback with older speakers and speakers with motor speech disorders remains unclear; additional studies targeting optimal feedback parameters are warranted.

Compliance with Ethical Standards

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Ethical Approval: The Institutional Review Board of University of Washington approved the study. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed Consent: Informed consent was obtained from all participants included in the study.

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