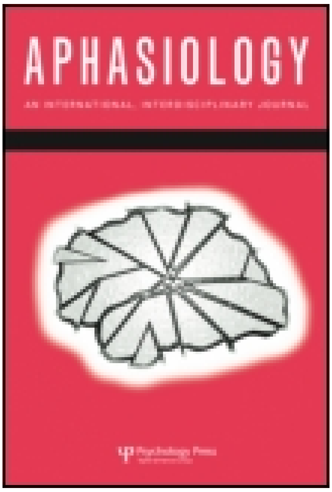

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Do principles of motor learning enhance retention and transfer of speech skills? A systematic review

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Do principles of motor learning enhance retention and transfer of speech skills? A systematic review

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Background: It is well documented in limb motor research that providing the optimal practice and feedback conditions can have positive outcomes for the learning of new movements. However, it remains unclear if the training conditions used for limb movements can be directly applied to the speech motor system of healthy adults and individuals with acquired motor speech disorders. Collectively these practice and feedback conditions are known as the *principles of motor learning* (PML), and they have recently been applied to the rehabilitation of motor speech disorders with promising results.
Aims: The purpose of this systematic review is to identify which PML have been examined in the speech motor learning literature, to determine the effectiveness of these principles, and to ascertain future lines of research.
Methods & Procedures: A systematic search of the literature was completed that involved the combination of a primary search term with a secondary search term. All articles were independently reviewed and scored by the first two authors. To guide the selection process strict inclusion and exclusion criteria were implemented. Additionally, authors used a 15-category evidence-rating system to judge the overall quality of each study. After the study was scored, points were totalled into an overall quality rating of high, intermediate, or low with respect to methodological rigour and interpretability.
Outcomes & Results: Seven articles met inclusion criteria, including three randomised controlled trials and four single-participant designs. Five of the articles focused on motor speech disorders, including investigations of apraxia of speech (four studies) and hypokinetic dysarthria from Parkinson's disease (one study), while two studies focused on speech motor performance in healthy adults. Five of the articles were judged to be of high quality while two were judged to be of intermediate quality.
Conclusions: Although limited, the current level of evidence for the application of the PML to speech motor learning in both healthy adults and individuals with motor speech disorders is promising and continued investigation is warranted.

Keywords: PML; Speech Rehabilitation; Motor Learning.

In the field of speech-language pathology the application of motor learning principles to speech movements has received increasing attention (Maas et al., 2008). Motor learning is a set of processes associated with practice or experience leading to relatively

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permanent changes in the capability for movement (Schmidt & Lee, 2005).The limb motor learning literature specifies conditions of practice and types of feedback, called principles of motor learning (PML) (Schmidt, 1988), that are known to enhance the learning and retention of novel movements. *Practice* conditions encompass issues such as practice amount, distribution, variability, and schedule, as well as attentional focus and target complexity. *Feedback* conditions include feedback type, frequency, and timing. There is robust evidence in the limb motor learning literature that the PML promote the acquisition, transfer, and retention of trained skills in healthy adults. Table 1 summarises the primary PML and illustrates the practice and feedback conditions that lead to optimal limb motor learning outcomes. In general, evidence from the limb motor learning literature supports the idea that the best learning outcomes are achieved when practice is distributed over time, there are a large number of practice trials, and the training stimuli are varied and randomised (see, for example, Baddeley & Longman, 1978; Park & Shea, 2003, 2005; Shea, Lai, Black, & Park, 2000; Wright, Black, Immink, Brueckner, & Magnuson, 2004; Wulf & Schmidt, 1997).

What remains unclear, however, is whether these PML apply to speech and, critically, whether they apply to disordered neurological systems. Accumulating evidence suggests that the PML facilitate the training (or retraining) of *limb* motor skills after neurological injury. Studies across a wide range of disciplines have provided supportive evidence that motor learning principles may improve the physical rehabilitation of individuals with stroke (Jonsdottir et al., 2010), traumatic brain injury (Croce, Horvat, & Roswal, 1996), cerebral palsy (Hemayattalab & Rostami, 2010), Alzheimer's disease (AD; Rice, Fertig, Maitra, & Miller, 2008), and Parkinson disease (PD; Onla-or &Winstein, 2008). However, these results are limited because they have examined only a restricted number of practice or feedback variables, and small

TABLE 1
Summary of the primary principles of limb motor learning

STRUCTURE OF PRACTICE
Massed practice (practise a given number of trials/sessions in a small period of time) versus
Distributed practice (practise a given number of trials/sessions over a longer period of time)
Blocked practice (different targets practised in separate, successive blocks, e.g., aaaa, bbbb) versus
Random practice (different targets are randomly intermixed, e.g., acbbcadabc)
Constant practice (practise target in same context) versus
Varied practice (practise targets in different contexts)
Low number of trials (i.e., < 50/target) versus
High number of trials (i.e., ≥ 50/target)
STRUCTURE OF FEEDBACK
Knowledge of Performance(feedback related to specific aspects of performance) versus
Knowledge of Results (feedback only related to the correctness of response)
High-frequency feedback(feedback after every trial) versus
Low-frequency feedback (feedback only after some attempts)
Immediate feedback (feedback immediately following attempt) versus
Delayed feedback (feedback provided with a delay, e.g., 5 seconds)

Bolded principles are those practice and feedback principles proven effective for long-term retention of trained limb movements (Schmidt & Lee, 2005).

groups of individuals with a specific severity level (typically mild-moderate). Thus, while the trend suggests rehabilitative benefit from the use of the PML, additional evidence is needed to understand whether these principles will help individuals from diverse clinical populations across severity levels.

Adding to the incomplete picture are studies which suggest that some principles of motor learning may actually be detrimental to rehabilitative efforts. For example, Dick, Hsieh, Dick-Muehlke, Davis, and Cotman (2000) examined two practice variables (random versus blocked practice and constant versus variable practice) in 58 persons with moderate-severe dementia from AD and 58 healthy older controls. Participants were taught to throw a beanbag towards a target from various distances. Results indicated that the control participants performed best with random, varied practice, a finding consistent with the principles of motor learning. The participants with AD, however, displayed optimal learning under constant practice conditions, and showed benefit from blocked practice, a finding counter to the motor learning principles. Thus there might be some neurological sequelae (e.g., pronounced memory impairment) that may negate any benefit from use of the PML during rehabilitative efforts. Researchers continue to investigate issues related to the candidacy of those who may, or may not, improve limb rehabilitation outcomes with the use of these principles.

It is therefore widely accepted that the principles of motor learning add considerable benefit to the training of limb motor skills in healthy adults and probable benefit to the limb rehabilitation of individuals with neurological impairment. The question now becomes whether these principles can make the theoretical and practical leap to speech motor learning. It is uncertain whether limb control and speech motor control *should* respond to practice/feedback variables in a similar manner given their disparate physiologic nature. Speech articulation is a highly complex and varied motor skill that is performed at an exceptionally rapid rate, without visual feedback of all of the speech structures. Furthermore, unlike limb movements, many speech movements do not involve joint action and require symmetric and synchronous movements of bilaterally innervated structures. Thus limb motor learning practice variables may lead to different results in speech motor learning tasks.

Although the speech and limb motor systems are dissimilar in their physiologic nature, schema theory can be used to describe the process by which both of these systems adapt and learn (Schmidt, 1975, 2003; Schmidt & Lee, 2005). Schema theory is a prominent theory of motor control and learning which provides a framework, encompassing generalised motor programs (GMPs) and parameters, for the learning and execution of movements. Schema theory defines movement as a stored set of generalised motor commands that are retrieved and sequenced to form motor programs, i.e., GMPs (Schmidt, 1975; Keele, 1968). GMPs represent the relative timing and force of muscle commands necessary for carrying out an action for a given class of movement. The details of motor execution, such as the absolute timing, force, and muscle selection, are determined by parameters assigned to a GMP. When motor learning occurs, changes are made to the internal state (i.e., GMPs and/or parameters) for movement. Thus motor speech disorders characterised by motor programming deficits, such as AOS, may benefit from exposure to the PML, as these principles are thought to facilitate changes in GMPs/parameters for speech production (Schmidt, 1975). The speech characteristics of AOS, such as sound-level distortions, substitutions, distorted substitutions, and slowed speech rate (Wambaugh, Duffy, McNeil, Robin, & Rogers,

2006) are hypothesised to result from deficits in activating and or parameterising GMPs (Ballard, Granier, & Robin, 2000; Clark & Robin, 1998). Furthermore there is evidence that motor programming is also disrupted in individuals with PD and cerebellar disease (Spencer & Rogers, 2005). Specifically, individuals with hypokinetic dysarthria from PD demonstrate deficits in the ability to switch, as well as maintain activation of motor programs. Therefore speech production is often filled with abnormally placed pauses, difficulty with progression through an utterance, and difficulty initiating articulation. Additionally, preliminary evidence suggested that individuals with ataxic dysarthria from cerebellar disease have difficulty activating motor programs prior to the initiation of speech, which may contribute to speech features such as disrupted prosodic patterns. If motor programming is indeed disrupted in these populations, the use of specific PML thought to facilitate learning and retention of GMPs and/or parameters may improve rehabilitation outcomes.

Research regarding the application of the PML to speech will help to guide clinical practice by identifying techniques most likely to enhance (re)learning and retention of speech abilities compromised by neurologic disease, as well as promote transfer of (re)learned skills. With that said, a small but growing body of literature is emerging that is focused on understanding the role of the PML on the motor speech system. Studies with the most scientific rigor provide controlled evidence, where the effect of a PML is examined by comparing the implementation of a specific principle thought to promote transfer and/or retention to a condition in which that principle is not implemented. For example, random practice is compared to blocked practice in the same study. Without such control, strong statements about the effects of PML cannot be made.

The purpose of this systematic review is to identify those studies that provide controlled evidence for the effects of the PML on speech production in both healthy adults and speakers with adult onset motor speech disorders. These studies will be rated for quality and results will be reported in terms of the strength of evidence of the various principles investigated.

METHOD

Search strategy

A systematic search of the literature was completed that involved the combination of a primary search term with a secondary search term. Primary terms included: principles of motor learning, motor learning, feedback, intensity, random practice, varied practice, distributed practice, target complexity, and external focus. Secondary words included: speech, dysarthria, apraxia of speech, intervention, and treatment. For example, "principles of motor learning" would be the first term paired with the second term "speech"; then "principles of motor learning" would be paired with "dysarthria". This procedure was repeated in each electronic database used in this review, allowing for the retrieval of a total of 2150 articles in our initial search between the years 1966 and 2011. The following electronic databases were included: PubMed, MEDLINE, PsychINFO, CINAHL, as well as ancestral searches of articles and textbooks.

Following the initial search, inclusion and exclusion criteria were applied. Inclusion criteria included: (1) study was published in a peer-reviewed journal and written in English, (2) study contained original data, (3) participants were healthy adults and/or adults with acquired motor speech disorders, (4) the study examined at least one PML, (5) a control condition was used, (6) measures of acquisition and retention or transfer were apparent, and (7) the trained behaviour was speech or speech related. Studies were excluded if they had exclusive focus on non-speech oral facial movement.

Relevant articles were first selected based on their titles. Although a complete investigation of inclusion and exclusion criteria could not be performed via title review, articles were selected for further review if the title did not present information that opposed the specified criteria (for example, articles were excluded if the title described children as the primary recipients). Following the title review 35 articles remained, and following abstract review 10 articles remained. These 10 articles were obtained and read by the first two authors. An additional three articles were excluded because they did not control for the PML being investigated. Thus a total of seven articles were selected for the final systematic review.

Evidence-rating system

An evidence-rating system was used (adapted from Burns & Miller, 2011) that consisted of a 15-category rating system (see Table 2). The overall rating was determined by awarding one point for each of the 15 methodological indices that were implemented in a given study. After the study was scored, points were totalled into an overall quality rating of high, intermediate, or low with respect to overall methodological rigour and interpretability (Table 3). All articles were independently reviewed and scored by the first two authors. Disagreements ($n = 3$) were discussed and resolved with 100% consensus and a final overall quality rating was assigned. The extracted data were compiled into a table of evidence that provides information regarding the study description, participant description, outcome measures, overall quality rating, and study conclusions (Table 4).

TABLE 2
Rating scale criteria based on Burns and Miller (2011)

Points	*Criteria*
1	Prospective study
1	Clear experimental controls
1	Blinding of assessors used
1	Blinding of participants used
1	Clear group description
1	Balanced baselines between groups or stable across participants
1	Target behaviours observable/measureable
1	Clear description of treatment/ experimental methods
1	Attrition rate
1	Clear description of immediate/acquisition outcomes
1	Statistical analysis described/appropriate
1	Appropriate reliability described/used
1	Appropriate validity described/used
1	Clear conclusion drawn from results
1	Clear description of retention/transfer outcomes
Total points possible = 15	

TABLE 3
Quality rating scale based on Burns and Miller (2011)

Quality rating	*Rating score range*	*Description of quality rating*
High	10 – 15	Study likely demonstrates appropriate design and use of experimental controls; results are more likely reliable and valid for interpretation
Intermediate	5 – 9	Study likely demonstrates flaws in design and experimental control; results may or may not be reliable and valid for interpretation
Low	0 – 4	Study likely has flawed design and ineffective use of experimental control; interpret results with caution

RESULTS AND DISCUSSION

Each study that met inclusion criteria will be discussed in detail below. Information is provided regarding participant characteristics, points awarded and/or lost based on rating scale criteria, and overall quality rating score, as well as a description of each experiment.

Study characteristics

The seven articles meeting inclusion and exclusion criteria span a 10-year period ranging from 2000 to 2010. The seven studies consisted of three randomised controlled trials (RCTs) and four single-participant designs (SPDs) and contained a total of 10 unique experiments. Of the seven articles, five focused on motor speech disorders, including investigations of AOS (four studies) and hypokinetic dysarthria from PD (one study), while two focused on speech motor performance in healthy adults. These studies investigated a variety of PML, including practice schedule, practice variability, target complexity, feedback frequency, and locus of feedback.

Participant characteristics

The total number of individuals with motor speech disorders included in this review was 27, ranging in age from 36 to 74 years. Of these individuals, 18 were diagnosed with mild to moderate speech and limb symptoms resulting from idiopathic PD and 9 individuals reportedly had AOS and concomitant aphasia. Individuals with AOS ranged in severity from mild to severe. The total number of healthy adults included in this review was 70, ranging in age from 18 to 41 years.

Overall quality rating

Overall, five of seven articles were judged to be of high quality while two were judged to be of intermediate quality. The majority of points were earned for prospective study, clear participant description, measurable target behaviours, clear description

TABLE 4
Table of evidence

	Study Description						*Participant Description*					*Outcome measures*				*Rating*		
Reference	*Phase Research*	*Research Design*	*Intervention*	*PML*	*Evidence of Control Measure*	*Number of Participants*	*Population/Type of MSD*	*Severity*	*Level of Participant Description*	*Age*	*Gender*	*Stable Basline Established*	*Acquisition Measures*	*Retention Measures*	*Transfer Measures*	*Quality Rating*	*Raw Score*	*Study Conclusions*
Knock et al. (2000)	Phase I	SSD	phonentic placement	practice schedule	yes	2	AOS/ apahsia	severe	good	36,65	m	yes	yes	yes	yes	high	12	• First well controlled investigation of the influence of PML on AOS • Effects are similar to those reported in limb research • Results provide clear justification for further investigation
Steinhauer & Grayhack (2000)	Phase I	RCT	vowel nasalisation	feedback frequency	yes	30	healthy adults	n/a	good	18–40	10m	n/a	yes	yes	yes	high	12	• High frequency feedback resulted in degraded retention and transfer compared to the low feedback group • Minimal to no differences between the 50% feedback group and the no feedback group
Adams & Page (2000)	Phase I	RCT	training novel speech	practice schedule variable practice feedback frequnecy	yes	40	healthy adults	n/a	fair	20–41	f	n/a	yes	yes	no	high	12	• Low frequency feedback enhanced retention of trained skills • Random and variable practice enhanced retention • Random and blocked practice produced similar acquisition rates

(*Continued*)

TABLE 4
(Continued)

	Study Description						Participant Description					Outcome measures				Rating		
Reference	Phase Research	Research Design	Intervention	PML	Evidence of Control Measure	Number of Participants	Population/Type of MSD	Severity	Level of Participant Description	Age	Gender	Stable Basline Established	Acquisition Measures	Retention Measures	Transfer Measures	Quality Rating	Raw Score	Study Conclusions
Adams et al. (2002)	Phase I	RCT	training novel speech	feedback frequency	yes	18	PD/ hypo	mild-moderate	fair	48–70	14m	n/a	yes	yes	no	high	12	• Training complex targets enhanced learning of complex and simple targets for one of two participants
Maas et al. (2002)	Phase I	SSD	modelling & repetition	target complexity	yes	2	AOS/ apahsia	moderate-severe	good	50,69	2f	no	yes	yes	yes	intermediate	7	• Low frequency feedback enhanced retention of trained skills two days after training
Hula et al. (2008)	Phase I	SSD	phonentic placement	feedback frequncy locus of feedback	yes	4/2*	AOS/ apahsia	severe moderate mild	good	70	3m	yes	yes	yes	yes	intermediate	7	• Inconsistent results due to a stimulus effect, stimuli were not equally balanced across conditions and phases • Results provided some support for the application of PML to speech motor learning
Katz et al. (2010)	Phase I	SSD	EMA	feedback frequency	yes	1	AOS/ aphsia	moderate	good	50	f	no	yes	yes	yes	high	12	• Feedback frequency did not have an effect on retention or transfer • Stimuli were few (3) and were not matched for difficulty, frequency, and/or phonotactic probability

hypo = hypokinetic dysarthria.
* only two participants were included in the timing of feedback treatment.

of treatment/experimental methods, low attrition rate, clear description of acquisition outcomes, and appropriate validity. The majority of points were lost for poor experimental controls, weak statistical analysis, and failure to identify if assessors and participants were blinded to experimental conditions.[1] An analysis of each study is provided below.

Description and quality of each PML study

Frequency of feedback (high vs reduced amount)

Feedback frequency refers to how often feedback is provided during training. High-frequency feedback, for example, may consist of providing feedback about movement outcomes after every trial (100%) as opposed to reduced-frequency feedback, where feedback may be provided every fifth or tenth trial. It is believed that high amounts of feedback make individuals dependent on the trainer's feedback, whereas low amounts of feedback allow individuals to develop their own internal assessment of a trained skill. In the current review 5 of the 10 experiments (from the seven studies) focused on the effects of feedback frequency on speech motor learning. These studies included three RCTs (Adams & Page, 2000; Adams, Page, & Jog, 2002; Steinhauer & Grayhack, 2000) and two SPD research studies (Hula, Robin, Maas, Ballard, & Schmidt, 2008; Katz, McNeil, & Garst, 2010).

Investigations of healthy adults. Two experiments investigated the effects of feedback frequency on the learning of novel speech tasks in healthy adults. Adams and Page (2000) compared the effects of feedback provided on every trial (high-frequency feedback) to summary feedback provided every fifth trial on the learning of a novel speech task in 20 young healthy females aged 20–41 years. Summary feedback is augmented information about each of a set of performance trials presented after the set is completed (Schmidt & Lee, 2005). The first group ($n = 10$) practised producing the phrase "Buy Bobby a poppy" at 2400 milliseconds, approximately two times slower than a normal rate of speech, in a block of 50 trials, while receiving feedback regarding utterance duration after every trial. A second group ($n = 10$) practised the same phrase at the same rate in a block of 50 trials, while receiving summary feedback after every fifth trial. Feedback was provided to both groups via graphing paper. Participants returned 2 days post training for retention testing of the trained rate. The primary outcome measure was absolute error. Results of this study demonstrated that summary feedback provided every fifth trial had better 2-day retention scores compared to feedback provided on every trial. However, during the *acquisition* phase, feedback on every trial resulted in an enhanced rate of acquisition when compared to summary feedback on every fifth trial. These results are consistent with the limb motor control literature (e.g., Nicholson & Schmidt, 1991; Vander Linden, Cauraugh, & Greene, 1993; Weeks & Kordus 1998; Winstein & Schmidt, 1990).

The Adams and Page (2000) study received a high quality rating (12/15 points). Three points were lost for failure to meet the following criteria: clear participant description, appropriate reliability methods, blinding of assessors. In regard to clear

[1] While it is understood that blinding participants to experimental condition is implausible in many behavioural investigations, if blinding is not utilised this should be justified, and the possible influence on results should be discussed (Weinberg & Kleinman, 2003).

participant description, the only information used to describe participants included gender and age. Ideally, standardised measures would have been administered to these participants to rule out neurological impairment. Also, authors failed to discuss reliability methods used and whether researchers were blinded to feedback conditions.

Steinhauer and Grayhack (2000) also examined effects of summary feedback, using a novel vowel nasalisation speech task, on 30 young healthy adults aged 18–40 years. Participants were randomly assigned to one of three groups where they received feedback on every trial (100%), feedback on every other trial (50%), or no feedback. Feedback was provided in the form of Knowledge of Results (KR) and entailed giving the learner knowledge of the accuracy of their attempt by showing them a percent nasalance score via a computer monitor. The task required participants to nasalise a sustained vowel (/i/) for 6 seconds in duration. Participants were then asked to perform a transfer task using a new vowel sound, /a/. Feedback was then provided via a nasalance score (which the authors referred to as KR). Outcome measures consisted of absolute error, absolute constant error, and variable error. Retention testing was conducted immediately following training at 5 minutes and at 1 day post training. Results demonstrated that participants receiving reduced feedback (50%) or no feedback had better 24-hour retention scores and exhibited better transfer than participants who received feedback on every trial. Results for 50% feedback are consistent with the limb motor literature in that reduced feedback results in improved retention. However, findings that 50% and no feedback resulted in similar learning outcomes are less common and were attributed to dynamical theories of motor control. Specifically, the authors felt it was possible that feedback was not as crucial given that production of the target vowel lies within the optimal range of nasalance. During acquisition, increased feedback resulted in decreased motor performance and learning, which is inconsistent with the limb motor learning literature.

The Steinhauer and Grayhack (2000) study received a high quality rating (12/15 points).Three points were lost for failure to meet the following criteria: appropriate reliability methods, clear conclusions drawn from results, and blinding of assessors. Results of the study were mixed in that not all conformed to traditional motor learning principles (i.e., results of the no feedback condition). Thus clear conclusions regarding the effects of feedback could not be drawn from results, as both the low feedback and no feedback conditions resulted in better overall retention and transfer of learned skills. Additionally, authors failed to discuss reliability methods used and address whether researchers were blinded to feedback conditions.

Investigations of individuals with Parkinson's disease. To date, there is only one published article that has examined feedback schedules in individuals with PD. Adams and colleagues (2002) compared feedback on every trial (100%) to summary feedback on every fifth trial for a novel speech task. A total of 18 individuals with "speech symptoms" from PD, ranging in age from 48 to 70 years, participated in this study and were randomly split into two groups; group one ($n = 9$) received feedback on every trial and group two ($n = 9$) received summary feedback on every fifth trial. Participants were asked to produce the phrase "Buy Bobby a poppy" approximately two times slower than a speech rate of 2400 milliseconds. Performance feedback was delivered via graphing paper and absolute error was used as the outcome measure. Retention testing was completed at 10 minutes and 2 days post training. Results revealed that participants who received high-frequency feedback showed faster rates of acquisition than those who received reduced feedback. However, those receiving summary feedback every fifth trial had better retention scores on both immediate and 2 days post retention testing than participants receiving feedback on every trial. Results indicate that reduced feedback enhanced learning. These findings lend support for the use of motor learning principles, specifically frequency of feedback, in the management of dysarthria.

This study received a high quality rating (12/15 points). Three points were lost for failure to meet the following criteria: clear participant description, appropriate reliability methods, and blinding of assessors. In regard to clear participant description, no details were provided as to the specific speech deficits observed in these participants; ideally results of standardised testing would have been reported. Finally, the authors failed to discuss reliability methods or to address whether researchers were blinded to feedback conditions.

Results of these three RCTs provide emerging evidence to support the premise that low-frequency feedback, compared to high-frequency feedback, enhances retention of trained skills. This finding is consistent with the limb motor learning literature.

Investigations of individuals with apraxia of speech. Two experiments examined the effects of feedback frequency on the relearning of speech targets (sounds, syllables, and/or words) in individuals with mild to severe AOS. In the context of a single-participant alternating treatment design consisting of two phases, Hula et al. (2008) examined the acquisition, retention, and transfer of speech skills in four participants with AOS under two different feedback conditions. Specifically, phase 1 included nonwords consisting of consonant vowel combinations (e.g., CV, CCV, CCVCCV, etc.) and phase 2 included nonwords consisting of vowel consonant combinations (e.g., VC, VCC, VCCVCC, etc.). Each phase contained two conditions: condition one included high amounts of feedback and condition two included low amounts of feedback. Multiple problems can occur when employing this type of design, such as carryover effects from one treatment phase to another. The authors argue that the study controlled for carryover effects because stable baseline measures were obtained before the initiation of phase 2, thus indicating that what was learned during phase 1 had stabilised prior to the initiation of phase 2.

In addition to the potential problems with carryover effects, the authors reported problems with stimulus effects. Stimuli were constructed according to each participant's level of ability; however, stimulus difficulty was not matched across treatment conditions for three of the four participants. Stimuli for Participant 1, characterised as having severe AOS, consisted of CV and VC syllables, where in phase 1 CV stimuli was targeted and in phase 2 VC stimuli was targeted. For this particular stimulus set the authors selected to train across manner of articulation (e.g., fricatives vs plosives). Motor learning theory predicts that generalisation should be observed within a specified motor program and across parameters of movement (Schmidt, 1975). Furthermore, a small body of research in speech motor learning supports the idea that manner of articulation corresponds to a motor program and place of articulation corresponds to parameters of movement (Ballard, Maas, & Robin, 2007; Maas et al., 2008). Thus training plosives with low-frequency feedback in phase 1 should not have an effect on fricatives, and therefore should not yield carryover effects.

Stimuli for Participant 2, one of the two participants characterised as demonstrating moderate AOS, consisted of two-syllable CCV nonwords in phase 1 and two-syllable VCC nonwords in phase 2. Condition one consisted of nonwords comprising fricatives and affricates, and condition two consisted of L-blends, such as "plu-plu". This set of stimuli might not be equally balanced. There is no evidence to support the idea that CCV or VCC nonwords comprising fricatives/affricates and CCV or VCC nonwords comprising L-blends are equal in difficulty.

Stimuli for Participant 3, also characterised as demonstrating moderate AOS, consisted of two-syllable CCV words in phase 1 and two-syllable VCC words in phase 2. Condition one consisted of front initial sounds (e.g., /b/) with the stress on the first syllable, and condition two consisted of back initial sounds (e.g., /k/) with the stress on the first syllable. This stimulus set might yield a stimulus effect, as back sounds such as /k/ and /g/ may be more difficult to (re)learn because the articulators/oral movements used to produce these sounds cannot be visualised as well as frontal sounds, such as /b/ and /p/. Furthermore, some of the stimuli in condition one shared manner of articulation with stimuli in condition two, and might have resulted in carryover effects from one stimulus set to another.

Phase 1 stimuli for Participant 4, characterised as demonstrating mild AOS, consisted of three-syllable initial S-cluster nonwords (e.g., CCCVCCVCCVC) in condition one and initial L-blend nonwords (e.g., CCVCCVCCV) in condition two. Phase 2 stimuli consisted of three-syllable back L-blends in condition one and three-syllable final S-cluster nonwords in condition two. This stimulus set might not have been equally balanced. There is no evidence to support that idea that the production of S-clusters involves the same level of difficulty as the production of L-blends, in particular stimuli consisting of S-clusters contained more phonemes (e.g., CCCV) than L-bends (e.g., CCV), resulting greater phonemic complexity.

Results of this investigation revealed inconsistent effects of reduced feedback on acquisition, retention, and transfer of trained speech tasks. For three of the four participants similar stimulus sets resulted in enhanced acquisition, retention, and transfer, regardless of feedback condition. Additionally, long-term retention data were collected on phase 1 stimuli 7–8 months after phase 1 treatment for participants 1 and 4 only. Previous findings were maintained; however, a slight decrease in ability was observed in Participant 1 for both feedback conditions. We agree with Hula et al. (2008) that these inconsistent results are likely indicative of a stimulus effect. In other words, it was difficult to isolate the effects of the PML because of pronounced stimulus effects.

The Hula et al. (2008) study received an intermediate quality rating (7/15 points). Eight points were lost for failure to meet the following criteria: clear experimental controls, clear description of acquisition outcomes and retention outcomes, clear conclusions drawn from results, appropriate statistical analysis, attrition rate, blinding of assessors, and blinding of participants. In a single-participant alternating treatment design participants are used as their own control. Thus performance in one treatment condition is compared to performance in another, allowing researchers to compare effects of treatment condition. However, as mentioned above, stimuli were not equally balanced across treatment conditions and therefore resulted in weak experimental controls. Furthermore, poor stimuli construction confounded the effects of feedback condition, yielding inconsistent acquisition, retention, and transfer results. Thus clear conclusions regarding the effect of feedback frequency on the learning of speech targets in individuals with AOS could not be made. To prevent stimulus effects, stimuli difficulty should be matched across treatment conditions. One way to do this would be to test participant stimulability for specific sounds and combinations of sounds, to be assured that the participant is equally stimulable for both stimuli sets prior to the initiation of treatment. Additionally, psycholinguistic factors, such as frequency (Kucera & Francis, 1967) and phonotactic probability (Storkel, 2001) should be taken into consideration during stimuli construction. In regards to statistical analysis, authors reported percent accuracy and results of visual inspection but failed to calculate and/or report effect sizes. Effect sizes quantify treatment outcomes for single-participant research studies and provide a means to compare treatment outcomes within and between individuals, as well as to compare the relative strength of various treatments (Beeson & Robey, 2006). Effect sizes can be used to measure direct treatment effects and retention of learned skills, as well as transfer of learned skills to untrained but related skills. Other statistical analyses, such as visual analysis, are susceptible to Type I error (Beeson & Robey, 2006). In regard to attrition rate, participants 2 and 3 were not available to participant in long-term retention testing. Lastly authors failed to report if assessors and participants were blinded to feedback conditions.

Katz et al. (2010) investigated the effects of visual augmented feedback provided by electromagnetic articulography (EMA) on the relearning of sound-level speech targets in one individual with AOS and concomitant moderate aphasia (severity rating for AOS was not specified, but scores and examples were provided). A secondary aim of this study was to investigate the effects of feedback frequency, using EMA, in the training of three speech motor targets in an individual with AOS. Effects of feedback frequency were investigated via treating the following speech motor targets /j, tʃ, θ/, in varying CVC contexts, where the participant received feedback on every trial (100%) for /j/ and /tʃ/ and reduced feedback (50%) for /θ/. Measures of control included probes of untrained sounds /br, sw/, with different manner of articulation than the trained speech motor targets, in CVC contexts. Results revealed treatment of speech motor targets receiving 50% feedback (/θ/) corresponded with relatively rapid acquisition and a low degree of overall maintenance, compared to treatment of speech motor targets receiving 100% feedback (/j/ and /tʃ/). These results are not consistent with the limb motor literature. Furthermore, the majority of the untreated "control" stimuli showed increased variability during the training phases of the three treated targets. The present data, however, must be considered with caution, as a small number of stimuli were involved and were not balanced across frequency conditions (Katz et al., 2010). Additionally, both /j/ and /tʃ/ were trained in the word initial position, whereas /θ/ was trained in the word medial position. Lastly, both /j/ and /θ/ revealed variable baselines prior to the initiation of treatment.

The Katz et al. (2010) study received a high quality rating (12/15 points). Three points were lost for not fulfilling the following criteria: balanced baselines across single participants, clear measures of experimental control, and clear conclusions drawn from results. Unstable baselines were evident for two of the three trained speech motor targets, /j/ and /θ/, therefore making it difficult to separate the effects of repeated exposure from that of treatment. Ideally treatment should not be initiated until baselines measures have stabilised. Although control measures were defined clearly by the authors, learning of the untrained "control" stimuli was observed. Thus, it is possible that improvements observed in these control words are either the result of repeated exposure or the result of carryover effects. Study limitations, such as unstable baselines, stimulus confounds and weak controls do not allow us to draw clear conclusions, regarding the effects of feedback frequency on the learning of speech motor targets in individuals with AOS, from these results.

Overall, the interpretability of these two studies is constrained by stimulus confounds. Further research is needed to clarify the effects of feedback frequency on speech motor learning in individuals with AOS.

Locus of feedback (immediate vs delayed)

Locus of feedback refers to the period in which feedback was provided relative to the completion of a task. Feedback can either be provided immediately after a participant completes a task (immediate feedback) or can be provided after a delay (e.g., 5 seconds after the participant completes the task). Delayed feedback is believed to be more conducive to the learning processes as it provides the learner with time to independently evaluate the motor act before receiving feedback. Only one speech motor learning study has examined feedback timing. This study, detailed below, focuses on individuals with AOS.

Investigations of individuals with apraxia of speech. In the context of a single-participant, alternating treatment design, consisting of two phases, Hula et al. (2008) completed a second experiment investigating the effects of timing of feedback on the acquisition, retention, and transfer of speech skills in two individuals with AOS. This study was completed using two participants (Participants 1 and 2) from the feedback frequency study mentioned above and used similar stimuli (not equally balanced across conditions). Once again, findings suggested inconsistent effects of feedback on the relearning of speech targets. For Participant 1, delayed feedback enhanced retention in phase 1 of treatment, whereas in phase 2 of treatment retention was enhanced by immediate feedback. Results of transfer to untrained stimuli, in both phases of treatment, did not reveal a stronger effect of either feedback condition. Rate of acquisition paralleled results of retention, where delayed feedback enhanced acquisition in phase 1 of treatment, but phase 2 of treatment acquisition was enhanced by immediate feedback. In contrast, Participant 2 revealed results consistent with that of the limb motor learning literature. Delayed feedback led to enhanced retention and transfer of trained skills in both phases of treatment, whereas immediate feedback led to enhanced rate of acquisition. Once again, stimulus effects might have influenced outcomes and therefore make it difficult to isolate effects of PML. Further research is needed to clarify the effects of timing of feedback on speech motor learning in individuals with AOS.

This experiment was conducted in combination with another experiment discussed above. Details regarding quality rating for the entire study are discussed earlier under the subheading “Investigations of individuals with apraxia of speech”, located in the section entitled “Frequency of feedback (high vs reduced amount)”.

Practice schedule: Blocked vs random stimulus presentation

Practice schedule refers to the order of stimulus presentation during practice; there are both random and blocked practice schedules. During blocked practice, different targets are practised in separate, consecutive blocks (e.g., BBBB, AAAA, CCCC). Blocked practice is considered the least complex of the two practice schedules, as it requires the participant to execute the same motor program for multiple consecutive trials. During random practice, however, stimuli are intermixed (e.g., ABAC, BCAC, CABA) and therefore require the retrieval and construction of a different motor program on every trial (Knock, Ballard, Robin, & Schmidt, 2000). Thus random practice facilitates the ability to discriminate differences in targets because new parameters for sound execution are selected from trial-to-trial. In contrast, blocked practice aids in initial skill acquisition because the parameters within a block are the same. The motor learning literature suggests that random practice promotes the acquisition of a more detailed representation of a motor act and as a result, facilitates generalisation and retention of trained skills (Ballard, 2001; Maas et al., 2008).

Investigations of healthy adults. One experiment investigated the effects of practice schedule on the learning of a novel speech task in healthy adults. Adams and Page (2000) compared random versus blocked practice schedules in their second comparison group consisting of 10 participants per condition between the ages of 20 to 41 years. As before, the investigators used an utterance duration task in which they had participants repeat the phrase "Buy Bobby a poppy" at approximately two and three times slower than a speech rate of 2400 milliseconds. Of the participants, 10 practised the phrase in blocked trials of 25 (i.e., 25 trials with the 2400 milliseconds slower target and 25 trials with the 3600 milliseconds slower target); the other 10 participants practised the phrase in randomised trials of 50 (i.e., the two different speech rates were intermixed). Both groups received feedback of speech duration via graphing paper 100% of the time. Absolute error was used as the primary outcome measure. Results revealed that participants in the random group displayed higher error rates than those in the blocked group during initial acquisition. However, as predicted, participants exposed to random practice displayed better 2-day retention scores than those in the blocked practice group. These results are consistent with findings from the healthy adult limb motor learning literature.

This experiment was conducted in combination with another experiment discussed above. Details regarding quality rating of the entire study are discussed earlier under the subheading "Investigations of healthy adults", located in the section entitled "Frequency of feedback (high vs reduced amount)".

Investigations of individuals with apraxia of speech. One experiment examined the effects of practice schedule on relearning speech targets in two individuals with severe AOS and aphasia. In the context of a single-participant, alternating treatment design Knock et al. (2000) completed the first controlled investigation of the application of PML to rehabilitation of AOS. The study consisted of two treatment conditions in which both random and blocked practice schedules were incorporated into a common treatment approach for AOS. Participant 1 underwent two phases of treatment (phase 1 and 2) and Participant 2 underwent only one phase of treatment. For Participant 1, phase 1 stimuli consisted of CV syllables and phase 2 stimuli consisted of VC syllables. Stimuli for Participant 2 consisted of CVC syllables. It was predicted that a random practice schedule would result in slowed acquisition rate, enhanced retention of trained skills, and enhanced generalisation to related but untreated speech tasks. Results demonstrated that a random practice schedule resulted in enhanced retention of trained targets for both participants and enhanced transfer of trained targets to novel stimuli in one participant. These results are consistent with the limb motor learning literature. However, rate of acquisition did not differ between the two treatment conditions; in other words, random practice did not appear to slow the initial acquisition of trained sounds in comparison to blocked practice.

This study received a high quality rating (12/15 points). Three points were deducted for not fulfilling the following criteria: appropriate statistical analysis, blinding of assessors, and blinding of participants. In regard to statistical analysis authors reported percent accuracy but failed to calculate and/or report effect sizes. Authors failed to discuss if assessors and participants were blinded to practice conditions.

Practice variability (variable vs constant)

Practice variability refers to either *constant* or *variable practice*. Constant practice consists of practising a behaviour in the same context repeatedly, such as producing sounds in isolation throughout a treatment session (i.e., the same phonetic context), whereas variable practice facilitates sound production over a range of possible contexts, such as producing CV, VC, CVC combinations, such as /ba/ or /ab/. Of the two, constant practice is considered least complex in that it focuses on only one movement variant, requiring the retrieval of only one parameter repeatedly. Thus variable practice is thought to facilitate motor learning in that it requires retrieval of different variants during practice vs the retrieval of the same variant over and over (Maas et al., 2008).

Investigations of healthy adults. One experiment investigated the effects of practice schedule on the learning of a novel speech task in healthy adults. Adams and Page (2000), using the same participants and protocol (i.e., saying "Buy Bobby a poppy" with target durations of 2400 and 3600 milliseconds) as previously discussed, investigated practice variability in their third comparison group by comparing single versus multiple task practice. The first group of participants ($n = 10$) was asked to attempt the 2400 millisecond target rate across all 50 trials (constant practice). The second group of participants ($n = 10$) was asked to attempt the 2400 millisecond target for the first 25 trials and the 3600 millisecond target for the last 25 trials (variable practice). Feedback was provided on 100% of the trials via graph paper. Results, using absolute error, showed similar acquisition patterns for both groups. However, upon completion of a 2-day retention test, participants who received a variable practice schedule produced the phrase with less error, thus indicating better overall learning of the task.

This experiment was conducted in combination with two other experiments discussed above. Details regarding quality rating of the entire study are discussed earlier under the subheading "Investigations of healthy adults", located in the section entitled "Frequency of feedback (high vs reduced amount)".

Target complexity (simple vs complex)

Target complexity or movement complexity has been investigated in limb motor learning in regards to simple vs complex movements, where simple movement refers to separately learning the parts that make up a full movement and complex movement refers to learning the whole movement at one time. Currently, evidence from the limb motor learning literature is inconsistent; there are studies to support both the use of training simple targets and those that support the training of more complex targets. Only one study has investigated the effects of target complexity on speech motor learning in individuals with motor speech disorders while controlling for complexity condition (Maas, Barlow, Robin, & Shapiro, 2002; Schneider & Frens, 2005).

Investigations of individuals with apraxia of speech. In the context of a single-participant, multiple-baseline, withdrawal design (ABCBC), Maas et al. (2002) investigated the effects of target complexity on the relearning of speech targets in two individuals with AOS and aphasia. Participant 1 was characterised as having moderate AOS and Participant 2 as having severe AOS. There were two treatment conditions: complex, including nonwords comprising complex clusters, and simple, including nonwords comprising simple singletons. Treatment stimuli for the complex condition consisted of three-element clusters (e.g., skweeve), and the stimuli for the simple condition consisted of singletons (e.g., keeve). Both participants were exposed to each treatment condition in different orders. Each participant served as her own control, as different stimuli sets were used in each treatment phase. Real word stimuli were used to measure transfer of trained speech targets to untrained but related targets. For Participant 1 the complex condition resulted in greater overall improvements in the production of simple and complex real and nonwords when compared to the simple condition. However, training of simple stimuli did result in improved production of both simple and complex real and nonwords, but it was to a lesser degree than that observed in the complex condition. Participant 2, however, did not demonstrate significant improvements in the production of complex real and nonwords, but did demonstrate improvements in the production of simple real and nonwords, regardless of treatment condition. Follow-up retention testing was collected at 1 and 2 months after treatment commencement. Results showed that the gains made during treatment were maintained, but did not increase. Follow-up retention measures were not collected for participant 2. Differences between participants level of impairment may explain conflicting findings. Further research is needed to clarify the effects of target complexity on the rehabilitation of individuals with AOS.

The Maas et al. (2002) study received an intermediate quality rating (7/15 points). Eight points were deducted for not fulfilling the following criteria: balanced baselines, clear measures of experimental control, clear description of retention outcomes, clear conclusions drawn from results, appropriate statistical analysis, attrition rate, blinding of assessors, and blinding of participants. In regards to statistical analysis, authors reported percent accuracy and calculated *p*-values. Reports of effects sizes would have been ideal for calculating improvements in a single-participant experimental treatment study. However, at least three data points from baseline and post-treatment testing are required to calculate effect sizes, and authors only obtained one baseline data point prior to the initiation of treatment for Participant 1. Thus effects size calculations were not possible. Furthermore, because a stable baseline was not established prior to the initiation of treatment for Participant 1, it is difficult to interpret the participant's baseline ability as well as the true effects of the first phase of treatment. Results of follow-up retention testing show that Participant 1 was able to maintain what was learned during treatment, but did not provide insight to the different effects of complex vs simple stimuli on retention. Participant 2 was not available for follow-up retention testing (i.e., attrition rate). In this single-participant design, participants acted as their own control; Participant 1 demonstrated learning of complex and simple stimuli in both treatment conditions (however, learning was greater in the complex condition) and Participant 2 demonstrated learning of simple stimuli in both treatment conditions (however, learning was greater in the simple condition) but no learning of complex stimuli. Furthermore the authors never addressed the concept of a control measure or control condition. Without a strong measure of control it is difficult to confirm that learning occurred as a result of the treatment versus effects of repeated exposure to stimuli. Lastly the authors failed to address if researchers or participants were blinded to treatment condition.

Overall, the mixed results observed between participants, unstable baselines, lack of long-term retention measures, and unclear control measures make it difficult to draw clear conclusions regarding the effect of stimuli complexity on the relearning of speech targets in individuals with AOS.

CONCLUSIONS AND RECOMMENDATIONS

Results from this systematic review demonstrate that the current level of evidence for the application of the PML to speech, in terms of practice and feedback variables, is promising and continued investigation is warranted. Future directions should include replication of current research, extension of investigations of young healthy adults to older healthy adults, extension of investigations to other motor speech disorders (e.g., ataxic dysarthria), and investigations of additional PML in both healthy adults and individuals with motor speech disorders.

Four of the seven studies reviewed here are SPDs and include a small number of participants. Although SPDs provide us with important information, they are typically criticised for lacking power and generalisability; replication of these studies could strengthen conclusions drawn from the current speech motor learning literature. Furthermore, three of the four SPDs revealed inconsistent results; thus further investigation is needed to clarify the effects of these PML on an impaired motor speech system.

Extension of investigations of young healthy adults to older healthy adults is needed. Currently, investigations of healthy adults have focused on young to early middle-aged speakers (18–41years). Thus two issues arise: first, the majority of individuals with acquired motor speech disorders do not fall into this age range, and second, the conclusions we draw from this young adult population do not necessarily reflect the learning patterns of older healthy adults.

The majority of current investigations have focused on the effects of the PML on speech motor learning in participants with AOS. Of the five studies reported in this review only one yielded consistent results that were supportive of the implementation of PML in the rehabilitation of AOS (Knock et al., 2000). AOS continues to be a topic of debate in regard to identifying the characteristics and the underlying impairment of the disorder. Furthermore, this motor speech disorder does not typically occur in isolation and is usually accompanied by dysarthria and aphasia (Duffy, 2005). Consequently it is difficult to isolate the effects of the PML on AOS alone. To clarify the effects of the PML on impaired speech motor systems, investigations of other populations with motor speech disorders should be considered.

There are a number of PML that have not been investigated in healthy adults including practice amount, practice distribution, attentional focus, target complexity, type of feedback, and the timing of feedback. Areas that have yet to be addressed in individuals with motor speech disorders include practice amount, practice distribution, practice variability, attentional focus, and type of feedback. Future investigations should incorporate these PML. Specifically, principles such as practice amount and practice distribution are of great interest to the field of speech-language pathology and would help to advance clinical practice. With continued investigation and a better understanding of these principles, clinicians will be more equipped to adapt therapeutic programmes to benefit the needs of individuals with motor speech disorders.

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