Exploring the Impact of Two Feedback Types on Speech Intelligibility, Precision, and Naturalness

Lauren Bislick, Ph.D., CCC-SLP, CBIS,[1]
Ashka Thakar, M.A., CCC-SLP,[2] **and**
Elizabeth Brookshire Madden, Ph.D., CCC-SLP[3]

ABSTRACT

This pilot study examined the impact of feedback type on learning a novel speech task, as measured by listener ratings, and will inform procedures for future investigations within a larger sample size. Twenty-four native monolingual English-speaking college-aged adults participated in a single training session to learn novel Hindi phrases. Participants were randomly placed into one of three feedback groups: knowledge of performance (KP), knowledge of results (KR), or a combined KP + KR condition. Participant performance was assessed at 1 day and 1 week post-training. Participant responses were audio recorded and judged for intelligibility, precision, and naturalness by native Hindi speakers, blind to the feedback conditions, via rating scales. At 2 days post-training, participants in the KP and KP + KR feedback conditions were rated as performing better than participants in the KR condition on all three perceptual measures. At 1 week post-training, participants in the KP feedback condition were judged to be superior across all three perceptual measures. Preliminary findings suggest that augmented feedback enhances learning, especially when skills are considered novel and learners are unable to rely on their own internal feedback. These results may have implications for the application of motor learning principles into clinical practice for persons with motor speech disorders.

KEYWORDS: feedback, motor learning, training, speech

---

[1]School of Communication Sciences and Disorders, University of Central Florida, Orlando, Florida; [2]AdventHealth, Florida; [3]School of Communication Sciences and Disorders, Florida State University, Tallahassee, Florida.

Address for correspondence: Lauren Bislick, Ph.D., CCC-SLP, CBIS, School of Communication Sciences and Disorders, University of Central Florida, P.O. Box 162215, Orlando, FL 32816-2215 (e-mail: Lauren.Bislick@ucf.edu).

Semin Speech Lang 2023;44:170–188. © 2023. Thieme. All rights reserved. Thieme Medical Publishers, Inc., 333 Seventh Avenue, 18th Floor, New York, NY 10001, USA
DOI: https://doi.org/10.1055/s-0043-1764201.
ISSN 0734-0478.

Learning Outcomes: As a result of this activity, the reader will be able to:

- Define and describe principles of motor learning.
- Explain the differences between two types of feedback, knowledge of performance, and knowledge of results.
- Provide examples of how to implement different feedback types, knowledge of performance, and knowledge of results, in a therapy session.

Motor learning is defined as a relatively permanent change in the ability to execute a motor skill due to practice and/or experience (Schmidt & Lee 2005). It allows us to develop skills, such as mastering a volleyball serve or fluently speaking a foreign language, and also safeguards the accuracy of simpler reflexive behaviors, such as ducking your head when something is suddenly coming your way (Cullen & Mitchell 2017). Researchers interested in motor learning seek to understand how people best acquire new motor skills and relearn or rehabilitate impaired movements.

Decades of research focused on limb motor learning has led to the identification of practice and feedback conditions shown to enhance the learning of trained movements (Schmidt et al. 2019). Together, these practice and feedback conditions are known as the principles of motor learning (PML; Schmidt 1988). Practice conditions include variables such as practice amount (large vs. small), distribution (massed vs. distributed), variability (variable vs. constant), and schedule (blocked vs. random), as well as attentional focus (external vs. internal) and target complexity (single vs. complex or part vs. whole). Feedback conditions include feedback type (knowledge of performance [KP] vs. knowledge of results [KR]), frequency (frequent vs. reduced), and timing (immediate vs. delayed) (Schmidt & Lee 2005; also see Bislick et al. 2012; Maas et al. 2008 for a brief review of the PML in speech). Overall, the extant literature suggests that these principles promote the acquisition, transfer, and retention of trained skills when practice consists of a large number of trails, is distributed over time, the training stimuli are varied and randomized, and when feedback consists of KR, is less frequent, and is delayed (e.g., Baddeley & Longman 1978; Park & Shea 2003, 2005; Shea et al. 2000; Wright et al. 2004; Wulf & Schmidt 1997). Schema theory of motor control (Schmidt 1975; Schmidt & Lee 2005) provides support for the positive impact of these principles on limb and speech motor learning.

Schema Theory

Schema theory, a prominent theory of motor control and learning, can be used to describe the process by which the limb and speech motor systems adapt and learn (Schmidt 1975, 2003; Schmidt & Lee 2005). Schema theory provides a framework, encompassing generalized motor programs (GMPs) and parameters, for the learning and execution of movements. Movement, as described by schema theory, includes the retrieval and sequencing of a stored set of generalized motor commands to form motor programs (i.e., GMPs; Keele 1968; Schmidt 1975). GMPs represent the relative timing and force of muscle commands necessary for carrying out an action for a given class of movement (e.g., throwing a ball), whereas the parameters assigned to a GMP represent the details of motor execution, such as the absolute timing, force, and muscle selection (e.g., speed or distance a ball is thrown). As mentioned earlier, true motor learning occurs when permanent changes are made to GMPs and/or parameters (Schmidt 1975)—and the PMLs are thought to facilitate these changes for both limb movement and speech production.

In speech, it is not clear which aspects are considered GMPs and which are considered parameters (Ballard et al. 2000; Maas et al. 2008). A GMP may represent the motor commands associated with a phoneme, a syllable, a word, or even a phrase, whereas speech rate, volume, and precision may be considered the parameters (Bislick et al. 2013; Maas et al. 2008; Varley et al. 2006). The speech difficulties observed in persons with motor speech disorders (MSDs) can also be described using schema theory. For example, the speech characteristics of apraxia of speech (AOS), that is, distorted sound and sound substitutions, slowed speech rate, and abnormal prosody, are hypothesized to result from deficits in activating and/or parameterizing GMPs (Ballard et al. 2000; Clark & Robin 1998). Research suggests that motor programming may also be impaired in persons with Parkinson's disease (PD) and cerebellar disease (Spencer & Rogers 2005). Specifically, persons with hypokinetic dysarthria from PD demonstrate deficits in the ability to maintain activation of motor programs and/or quickly switch between motor programs (Spencer & Rogers 2005), as evidenced by abnormally placed pauses during speech production and trouble with speech initiation and progression through an utterance. Speech characteristics observed in persons with ataxic dysarthria due to cerebellar disease, such as impaired prosody and irregular articulatory breakdown, may be attributed to problems with activating GMPs prior to the initiation of speech (Spencer & Rogers 2005). Thus, if motor programming is indeed disrupted in these populations, the use of PML may positively impact rehabilitation outcomes by facilitating learning, retention, and transfer of trained skills. However, the implementation of PML for speech learning (and relearning after brain injury) is understudied, particularly in comparison to the study of limb motor learning.

Many researchers and rehabilitation experts suggest that the key to understanding how to improve disordered movement can be found through investigations examining how normal movement is controlled (e.g., Levin & Demers 2021). The investigation of PML began with neurologically healthy individuals, both young and older adults, and has been extended to persons with physical and neurological damage. The extant literature provides strong support for the application of PML to enhance limb motor learning in neurologically healthy individuals (e.g., Levin & Demers 2021; Schmidt & Bjork 1992; Schmidt & Lee 2011). The benefit for persons with neurological injury is also supported, yet it is not as straightforward given the heterogeneity in these populations. Findings suggest that the use of PML has probable benefit to the rehabilitation of limb movement for populations with neurological injury or disease. In particular, the application of PML to limb motor learning (or relearning) has shown promising outcomes in individuals with a history of stroke (Jonsdottir et al. 2010; Molier et al. 2010; Woldag et al. 2010), traumatic brain injury (Croce et al. 1996), Alzheimer's disease (AD) (Rice et al. 2008), PD (Onla-or & Winstein 2008), cerebral palsy (Hemayattalab & Rostami 2010), and developmental delay (Rice & Hernandez 2006). These studies, however, include small sample sizes, are limited in range of severity (typically mild-moderate), and do not address all the PML. Thus, while it is accepted that the PML enhance the training of limb motor skills in healthy individuals and can be extended to some individuals with neurological damage, continued research is warranted to further explore the benefit of all PML in populations with neurological injury. It is especially important to continue these investigations in impaired populations to address the impact of individual variables that may influence patient performance, such as severity of impairment, cognitive resources (i.e., attention and memory), and time post–onset injury or diagnosis. Importantly, findings from the limb motor learning literature have raised awareness of the PML across disciplines and led researchers to explore the application of the PML to speech motor learning in neurologically healthy adults and persons with acquired AOS and dysarthria.

When applying the PML to speech production, it is important to consider the similarities and differences of the speech and limb motor systems. As discussed by Bislick and colleagues (2012), speech articulation is a highly complex and varied motor skill that is performed at an exceptionally rapid rate, without visual feedback of all the speech structures, and, unlike some limb movements, speech movements require symmetric and synchronous movements of bilaterally innervated structures that do not involve joint action. However, as reported by Weir-Mayta et al. (2019 2022), the similarities between the two motor systems in their requirements for movement planning, trajectory, timing, coordination, sequencing, and biomechanics (Grimme et al. 2011) provide support for applicability of PMLs to facilitate motor learning in speech as well. These similarities have motivated the investigation of the application of PMLs to speech in healthy young adults (Adams & Page 2000; Jones & Croot 2016; Kim et al. 2012; Lowe & Buchwald 2017; Steinhauer &Grayhack 2000; Scheiner et al. 2014) and healthy older adults (Kaipa et al. 2017; Weir-Mayta et al. 2019. 2022). Many of these investigations have employed a foreign language task as the targeted motor skill (e.g., Korean phrases), while others addressed the modification of speech features (e.g., speech rate, nasality) or production of novel words (non-words) using combinations of English phonemes. Findings from most of the studies examining PML in young adults suggest that the application of PML benefits speech motor learning similarly with limb motor learning. Investigations in older adults have yielded inconsistent results, with some showing outcomes similar to limb studies, and others yielding inconsistent findings (Weir-Mayta et al. 2022).

Investigation of PML in persons with acquired MSDs, including acquired AOS from stroke (Austermann Hula et al. 2008; Ballard et al. 2007; Bislick 2020; Bislick et al. 2013, 2014; Katz et al. 2010; Knock et al. 2000; Van der Merwe 2011; Wambaugh et al. 2013 2014) and hypokinetic dysarthria from PD (Adams et al. 2002; Spielman et al. 2007), has also been conducted. In particular, a small but growing body of literature, primarily focused on AOS, suggests that the implementation of the PML during speech training and/or treatment may enhance (re)learning and retention of trained speech skills (Austermann Hula et al. 2008; Katz et al. 2010; Knock et al. 2000; Wambaugh et al. 2013; 2014). In a recent systematic review of the AOS treatment literature, Ballard and colleagues (2015) identified 14 treatment studies, out of the 26 treatment studies reviewed, that included PML. Several published studies have explicitly assessed specific PML in persons with AOS (e.g., Austermann Hula et al. 2008; Bislick et al. 2013; Katz et al. 2010; Knock et al. 2000; Wambaugh et al. 2013, 2014), while others have incorporated PML into their treatment protocols (e.g., Bislick 2020; Bislick et al. 2014; Van der Merwe 2011).

SPEAKERS WITHOUT IMPAIRMENT

As discussed by Lowe and Buchwald (2017) and others (e.g., Weir-Mayta et al. 2019), findings from studies that examine the effects of the structure of practice and/or nature of feedback on acquisition and retention in speakers without impairment can inform translation to clinical populations. The benefits of working with neurologically healthy populations include the opportunity to engage a larger sample size, perform more group analyses, and collect data from a relatively homogeneous group—in terms of ability level and typically functioning cognitive processes required for learning. From here, we can then extend investigation to individuals with neurological impairment, assess similarities and differences, and better understand how differences within clinical populations (e.g., attention) may impact performance. A challenge, when working with neurologically healthy populations, is that participants tend to learn new speech motor behaviors quickly and with a high degree of accuracy, thereby leading to ceiling effects which can make it difficult to observe potential effects of an experimental manipulation (Lowe & Buchwald 2017, p. 1713). It is, therefore, necessary to employ stimuli that provide enough of a challenge to task the intact speech motor system (e.g., Lisman & Sadagopan 2013; Sasisekaran et al. 2010). To achieve this goal, studies have employed the use of novel nonnative stimuli, such as nonnative sounds, words, and phrases, which can challenge speakers without impairment with novel sequencing of the articulators, defy common phonotactic principles found in the speaker's native language, and include nuances in prosodic aspects of speech production. Thus, the production of novel nonnative stimuli will require more explicit motor learning than real or nonword stimuli from a speaker's native language (Lowe & Buchwald 2017).

Feedback Type

Past investigations (see Bislick et al. 2012; Maas et al. 2008) have compared the aspects of practice variability, stimulus complexity, attentional focus, and feedback frequency and timing on speech motor learning in neurologically healthy adults and persons with MSDs, whereas only one PML study has compared the different types of feedback information, KP and KR, on speech performance (Ballard et al. 2012). Feedback type, or the type of augmented feedback provided during limb or speech training/treatment, typically by a trainer or therapist, is of particular interest as it has important implications for clinical application. There are two main types of feedback, KP and KR (Schmidt & Lee 2005; van Vliet & Wulf 2006). Feedback in the form of KP provides specific information about how a movement should be modified to successfully achieve the target (e.g., "move your tongue forward"; Lauber & Keller 2014). KP may also include biofeedback, such as using a mirror to watch the movement or other visual or auditory feedback about movement accuracy in relation to the target. Thus, there is some variability in how KP feedback is provided and the amount of detail that can be obtained from that feedback (e.g., biofeedback vs. auditory instruction, or a combination of the two). Feedback in the form of KR, however, consists of information about the general outcome of a movement (e.g., "close, but not quite right," "You've got it!") after a task has been completed and may refer to a deviation from a spatial or temporal goal (Lauber & Keller 2014; Maas et al. 2008). Although each of these feedback types can serve as a basis for error correction, the limb motor learning literature indicates that they may address learning in different ways (Maas et al. 2008; Maier et al. 2019). Specifically, KP is thought to facilitate learning during the acquisition phase, whereas KR is thought to enhance retention of trained skills (Schmidt & Lee 2005; Young & Schmidt 1992). It is important to note, however, that KR is often inherit with KP feedback. In other words, when KP is provided, general movement accuracy is also conveyed (Knock et al. 2000).

While KR is often associated with superior performance post-training, results of limb learning studies that have compared the benefits of KR and KP on the retention of trained skills are equivocal (Kaipa 2013; Sharma et al. 2016) and suggest that the influence of feedback type on motor learning may be dependent on the task (Newell & Carlton 1987; Newell et al. 1987, 1983; Ronsse et al. 2011; Sharma et al. 2016). As discussed by Sharma and colleagues (Newell & Carlton 1987), KP may be superior to KR when (1) skill execution requires specified movement characteristics (e.g., gymnastics); (2) skills that require complex coordination must be improved or correct (e.g., playing the saxophone, speech production); (3) the focus is on the movement or specific muscle activity involved in mastering the skill (e.g., tennis serve); or (4) KR is redundant with intrinsic (vs. augmented) feedback. In contrast, KR may be superior to KP when (1) learners use KR to compare with their own intrinsic feedback about task performance; (2) learners cannot determine the outcome of performing a skill via intrinsic feedback; (3) KR motivates the learning (especially when KR is positive; e.g., Saemi et al. 2012); and/or (4) when the goal is to create a discovery learning practice environment (i.e., trial and error method of skill performance). Additionally, although yet to be examined systematically, other motor learning variables may impact the benefit of feedback type on skill learning, for both limb and speech motor learning. For example, studies have shown interactions between feedback frequency and practice schedule (e.g., Adams & Page 2000) and feedback frequency and task complexity (e.g., Sidaway et al. 2012) on (re) learning. Thus, these same variables may also impact the influence of feedback type on speech (re)learning.

A small number of studies have examined feedback type as it relates to speech motor learning; however, only one study has compared the effect of different types of feedback on speech learning. Ballard and colleagues (2012) examined the impact of two feedback conditions, (1) a combined feedback KR and KP condition (KP in the form of biofeedback via electropalatography) and (2) a KR only (no KP) condition, on the acquisition and retention of a trilled Russian /r/ in monolingual, neurologically healthy English speakers. Participants in each group received high amount of feedback on all trials. Participants in the biofeedback plus KR group received both types of feedback simultaneously, after every trial. The authors report no between-group differences in accuracy on 1 day post-training (1 day after the last training session); however, the 100% KR-only group (no KP) demonstrated superior performance at 1 week post-training (1 week after the last training session) compared to the KR plus KP group. These results suggest that KR feedback facilitates retention of a trained novel speech task better than the combined KR and KP (biofeedback) condition. The authors attribute the lower retention rates in the combined KR and KP group to the continuous delivery of biofeedback (i.e., KP) during skill acquisition.

In numerous everyday learning or relearning environments, KP is used over KR, when instructors want to direct the attention of the learner to the essential elements of the movement pattern or of the context in which that pattern occurs (Nunes et al. 2014). In clinical practice, professionals often take the approach of providing more detailed feedback early on during therapy, while the learner develops an understanding of task expectations. As therapy progresses, feedback often becomes less detailed, more like KR, as the learner is encouraged to self-monitor, identify, and self-correct errors that occur. Given their common use, further research comparing the effects of KP and KR feedback is critical to better understand the influence of these two feedback types on different aspects of speech learning. Specifically, examining KP feedback and KR feedback independently, and in sequential application, starting with KP and moving to KR (with no KP), may provide insight as to which type of augmented feedback, or a combination of the two, is most beneficial for the learning and rehabilitation of speech skills.

The primary aim of this pilot study was to examine the effect of three feedback conditions on novel speech learning in neurologically healthy adults, as measured by listener ratings of intelligibility, precision, and naturalness at 1 day and 1 week post-training. The three feedback conditions consisted of (1) KP only, (2) KR only, and (3) a combined condition (KP + KR), moving from KP initially to only KR. Given that both KP and KR are thought to assist learning in different ways (skill acquisition and skill retention, KP and KR, respectively Schmidt and Lee, 2005), we predicted that speech learning, and therefore listeners' perception of the participant's speech, would be enhanced in the combined KP + KR condition. This study serves as pilot work to inform procedures for future investigations with older adults in a larger sample size. The long-term goal of this work is to inform the use of different feedback types to assist with speech rehabilitation in speakers with MSDs.

METHOD

This research received ethics approval from the Institutional Review Board of the University of Central Florida.

Participants

Twenty-four neurologically healthy female college students participated in this study. Participants were included in the study if they met the following criteria: (1) monolingual English speakers; (2) 18 to 40 years old; (3) passed an audiometric pure-tone, air-conduction screening at 25-dB HL at 500, 1,000, 2,000 and 4,000 Hz in both ears; and (4) performed within normal limits on the Montreal Cognitive Assessment (MOCA; version 7.1; Nasreddine et al. 2005). Participants were excluded from the study if they had a positive history of developmental or acquired communication impairment and/or previous exposure to the Hindi language; each was determined via participant self-report. Please see Table 1 for participant demographic information organized by group.

Twenty native-Hindi speakers, blind to study conditions, acted as expert raters and judged participants' productions of the trained stimuli, at 1 day and 1 week post-training, using measures of intelligibility, precision, and naturalness via a 7-point rating scale. Raters consisted of 9 males and 11 females and ranged in age from 20 to 48 years ($M = 33$ years; standard deviation [SD] $= 11.21$) and had 14 to 20 years of education ($M = 16$; $SD = 3.01$). Included raters spoke the same Hindi dialect as that taught to the study participants (also spoken by the second author) and reported adequate hearing acuity, no history of developmental or acquired communication impairments, and access to reliable internet and computer audio. Details regarding the raters' scoring procedures are described in "Data Analysis" section.

Table 1 Participant demographics

Pt. ID	Group	Age	MOCA
7	KP	20	29
8	KP	21	29
9	KP	19	27
10	KP	22	26
17	KP	22	29
20	KP	20	27
23	KP	21	29
26	KP	23	29
1	KR	19	29
2	KR	21	27
3	KR	40	30
6	KR	20	27
14	KR	20	30
19	KR	22	27
21	KR	21	28
25	KR	20	30
12	KP + KR	22	30
13	KP + KR	20	29
15	KP + KR	19	27
16	KP + KR	24	30
18	KP + KR	22	30
22	KP + KR	20	27
24	KP + KR	21	28
27	KP + KR	19	28
	Mean (SD)	**21.70 (4.19)**	**28.42 (1.28)**

Note: MOCA, Montreal Cognitive Assessment (Nasreddine et al. 2005)—MOCA scores of 26 and up are considered within normal limits; Pt., participant; SD, standard deviation. Bold text at the bottom of the table represents the means and standard deviation for participant age and performance on the MOCA.

Design

In the context of an experimental group design, across three sessions, the influence of feedback type on the intelligibility, precision, and naturalness of a novel speech task was explored at 1 day and 1 week post-training. This design replicated that of Kim and colleagues (2012). The 24 participants were randomly assigned to one of three feedback groups: KP-only group ($n = 8$), KR-only group ($n = 8$), and KP + KR group ($n = 8$). All participants completed one 1-hour training session, followed by two testing sessions. Testing occurred at 1 day post-training and 1 week post-training. This training and testing schedule followed that of previous studies examining the application of PML limb and speech learning (e.g., Anderson et al. 2001; Bislick et al. 2013; Kim et al. 2012; Schmidt & Bjork 1992; Weir-Mayta et al. 2019). All sessions were audio recorded and assessed for fidelity.

Stimuli

The training stimuli consisted of 10 Hindi phrases, ranging from three to four words. The phrases varied in frequency of occurrence and phrase type. For example, a highly frequent phrase trained in this study included the question "How are you today?" (आप कैसे हो)/ɑp kæse hθ/. A less frequent phrase trained in this study was the statement "Beauty of nature" (प्रकृति की सुंदरता)/prək̮rʌtɪ kɪ sʊnd̪ərʌt̪ɑ/. Trained phrases contained a spectrum of phonetic sounds and sound combinations native to the Hindi language (Samudravijaya et al. 2000). As previously mentioned, using a foreign language, rather than participants' native language or sounds native to participants, can increase the complexity of the motor task, and help facilitate new learning. Since the focus of this study was on speech, not language, the meaning of the phrases was not shared with the participants until the study had been completed.

Procedures

All participants were administered the MOCA (Nasreddine et al. 2005) and had their hearing screened within 2 weeks prior to the start of the training. The assessment, training, and two testing sessions took place in a quiet office space at the University of Central Florida. During the training session, 10 Hindi phrases were verbally presented to each participant by the primary research assistant, a native-Hindi speaker (second author and second-year graduate student of speech-language pathology). The same native-Hindi speaker worked with each participant for all three sessions to maintain consistency in the delivery of stimuli. The Hindi phrases were presented live to simulate clinical practice and allow the second author to accurately implement each unique protocol and respond appropriately to the participant's responses. A written procedural protocol, specific to each feedback condition, was used in every training session to ensure fidelity of the training protocol for each participant and feedback condition. Participants were instructed to "repeat each phrase after the model as accurately as possible." All participants completed 100 trials. Phrases were pseudo randomized into blocks of 10, for a total of 10 productions of each phrase during the training session. Regardless of feedback group, all participants received low-frequency feedback, 20%, during the training phase, following that of previous studies on speech motor learning (Adams & Page 2000; Adams et al. 2002). Order of stimuli presentation was randomized within and across conditions for each participant at all three timepoints (training, 1-day testing, 1-week testing). Participants were requested to repeat each phrase after the second author provided a model of the target phrase. More specifically, the second author would provide a model and the participant would follow with one repetition of the target. Stimuli were presented in serial fashion, with a brief pause after each production, unless feedback was being provided. See below for more details regarding feedback.

KNOWLEDGE OF PERFORMANCE GROUP

During the training phase, the eight participants received feedback on 20% of trials. Specifically, the second author used pictures of the mouth and articulators to provide detailed feedback about placement of the articulators and verbal instruction, such as "Your tongue needs to go here to make that sound," "The nasality of that sound was very good."

KNOWLEDGE OF RESULTS GROUP

During the training phase, the eight participants in this group received KR (no KP) feedback on 20% of trials. In particular, the second author provided general feedback about production accuracy, such as "You're doing great," "We sound the same," or "That is not quite right."

KP + KR GROUP

During the training phase, the eight participants in this group received KP + KR feedback on 20% of trials. In this condition, the first 50 trials practiced received KP feedback and the second 50 trials received KR (no KP) feedback. The same phrases were practiced in each condition (5 trials of each of the 10 phrases in each feedback condition, for a total of 10 trials of each phrase). The order of type of feedback, KP first and then KR, was chosen for two reasons. First, as discussed in the "Introduction," there is theoretical support that KP is most beneficial during the initial learning of a task, whereas KR promotes retention and generalization. Second, in clinical practice, clinicians often begin with more detailed feedback and then fade that level of detail away, as the task becomes known, to encourage self-monitoring.

TESTING

During the 1-day and 1-week post-testing session, the same 10 Hindi utterances used during the training session were verbally presented by the second author. Stimulus presentation was again randomized within and across conditions and phases. Participants were asked to repeat the utterances after the model provided by the second author as accurately as possible; a delay was not imposed on the speaker. This method of eliciting a speech sample and assessing speech motor learning is consistent with speech motor learning studies in neurologically healthy speakers and speakers with MSDs and is one method in which speech learning is measured in clinical practice. Feedback was not provided to the participants during the testing sessions. All phrases produced by the participants during the testing phase were recorded using an Olympus digital voice recorder (WS-852) with an external headset microphone (Audio-Technica ATM75).

Data Analysis

A total of 480 de-identified audio recordings of participant productions of trained target phrases from 1-day and 1-week testing were randomized within and across conditions and presented to the 20 expert listeners (i.e., Hindi-native raters) via Qualtrics software (https://www.qualtrics.com), an online survey platform. The recorded phrases, the participants' productions only, were auditorily presented along with the associated written target phrase, written in both English and Hindi. Prior to listening and scoring the audio recordings of participant responses, raters were provided with written and auditory instructions for how to complete the ratings, as well as three practice trials. Feedback was not provided to the raters about their selections. Once the raters completed the practice trials they were permitted to move on to the experimental stimuli and complete the study. Presentation of stimuli was randomized within Qualtrics. Given the large number of stimuli and to avoid listener fatigue, the data were presented to listeners via two separate Qualtrics surveys that could be completed at different timepoints. Raters were asked to complete the two surveys within a 72-hour period and were encouraged to only complete ratings in a quiet environment when they were able to focus. Raters were provided with contact information and encouraged to contact the authors if they had questions or difficulty with the protocol. Following the procedures of Kim et al. (2012), who also assessed the impact of specific PML on listener ratings of a novel speech task, raters in the current study were asked to judge each recording on three constructs, intelligibility, naturalness, and precision using a 7-point rating scale. Each scale offered seven different options to choose from, ranging from low to high performance (e.g., 1 = very unnatural; 7 = very natural). The three constructs were defined and described to each rater as follows:

- *Intelligibility*—Intelligibility was defined as how clearly a person speaks so that his or her speech is comprehensible to the listener (Leddy 1999). Raters were asked to rate intelligibility based on the degree to which they understood the speaker (Duffy 2013, p. 78).
- *Precision*—Precision, referred to articulatory precision, was defined as how clearly a person articulates their spoken productions (Lubold et al. 2019). Raters were asked to rate precision based on the degree to which the speaker accurately produced the sounds in the words.
- *Naturalness*—Naturalness was defined as how one's speech conformed to the "listener's standard of rate, rhythm, intonation, and stress patterning, and if it conforms to the syntactic structure of the utterance being produced" (Yorkston et al. 1999, p. 464). Raters were asked to rate naturalness based on the degree to which the speaker sounded like a native Hindi speaker.

PROCEDURAL FIDELITY

To assess fidelity of the training phase for the three feedback conditions, a trained research assistant listened to each of the recorded training sessions offline, using the written protocol for each condition as a checklist. No deviations from the planned protocol for each feedback condition were observed.

RELIABILITY

Cronbach's coefficient alpha was run to determine the internal consistency of ratings across the three listener rating scales. Values for Cronbach's coefficient alpha for the listener ratings across the 24 participants for each speech-dependent variable (intelligibility, precision, naturalness) was ≥ 0.93 at 1 day and ≥ 0.86 at 1 week post-training. These scores indicate a high level of internal consistency within raters for the three scales with this specific sample at these two timepoints. Kendall's coefficient of concordance, W (Gibbons & Chakraborti 2011; Laerd Statistics 2016), was run for > 30% of the data to determine interrater agreement on ratings of intelligibility, precision, and naturalness for the 20 participants. Raters statistically significantly agreed in their ratings, $W = 0.55$, $p < 0.000$.

STATISTICAL ANALYSIS

Two-way repeated measures analysis of variances (ANOVAs) was run to assess the impact of feedback type (KP group, KR group, or KP + KR group) on ratings of intelligibility, precision, and naturalness for the two timepoints, 1 day and 1 week post-training. Post hoc multiple comparisons with a Bonferroni correction were conducted to further examine significant findings.

RESULTS

All 24 participants completed a 1-day training session, followed by a testing session at 1 day and 1 week post-training. A total of 480 de-identified speech samples, 10 from each participant for each retention testing phase, were used to examine the effect of feedback condition on learning and retention of a novel speech task. Twenty native Hindi-speaking raters judged the quality of all 480 recordings using the three rating scales for intelligibility, precision, and naturalness.

Training Data

While the purpose of this study was not to assess participant performance during the training session, it is important to demonstrate that there was an impact of training on initial acquisition during the training session. Changes in performance during the training session were determined offline by a native Hindi speaker, blind to the study conditions. Specifically, participant productions were transcribed and scored for accuracy of word production offline. For each participant, percent accuracy of the first 10 productions was compared to percent accuracy of the last 10 productions (Fig. 1). All participants demonstrated positive changes in word accuracy during their training session. Participants in the KP group demonstrated a small effect of immediate training ($d = 2.82$) when comparing accuracy of initial productions (M = 45.16%; SD = 14.43) to accuracy of final productions (M = 82.66%; SD = 12.06), a difference of 35.50% accuracy. Participants in the KR group demonstrated a small effect of training ($d = 2.13$) when comparing accuracy of initial productions (M = 54.30%; SD = 12.31) to accuracy of final productions (M = 78.50%; SD = 10.34), a difference of 24.19% accuracy. Finally, participants in the KP + KR group demonstrated a small effect of training ($d = 2.44$) when comparing accuracy of initial productions (M = 52.42%; SD = 10.73) to accuracy of final productions (M = 80.65%; SD = 12.31), a difference of 28.23% accuracy. These data indicate that participants across all three groups showed improvement in the accuracy of their productions of the trained Hindi phrases from the beginning to the end of the training session. The main findings, reported later, focus on the effects of feedback type on the perceptions of native speakers of Hindi at 1 day and 1 week post-training.

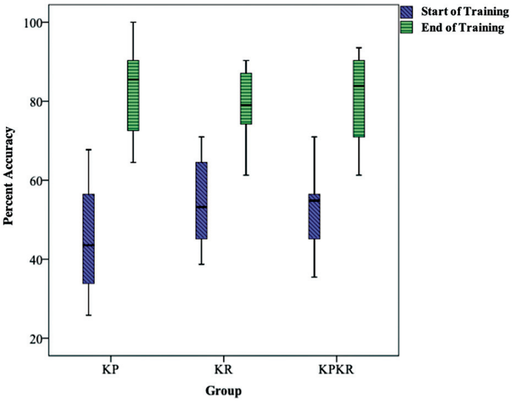

Figure 1 Participant accuracy during training session: comparing the first 10 productions to the last 10 productions.

Results of Listener Ratings

A two-way repeated measures ANOVAs was run to compare the effect of feedback type (KP, KR, and KP + KR) on listener ratings of intelligibility, precision, and naturalness across two timepoints, 1 day and 1 week post-training. Please see Fig. 2 for the group statistics obtained for the dependent variables (intelligibility, precision, and naturalness) across the three feedback conditions and assessment timepoints.

INTELLIGIBILITY

A two-way repeated measures ANOVA was run to determine the effect of different feedback conditions on listener ratings of intelligibility at two timepoints. Analysis of the studentized residuals showed that there was normality for the KR and KP conditions at both timepoints ($p > 0.05$), but not the KP + KR condition ($p = 0.026$), as assessed by the Shapiro–Wilk test of normality. There were no outliers for all feedback conditions at both timepoints, as assessed by no studentized residuals greater than ± 3 SDs. The assumption of sphericity was violated, as assessed by Mauchly's test of sphericity, $\chi^2(2) = 15.023$, $p = 0.001$. Therefore, the Greenhouse–Geisser correction was applied ($\epsilon = 0.851$). There was a statistically significant interaction between feedback type and time on listener ratings of intelligibility, $F(1.702, 134.447) = 3.658$, $p < 0.035$. Therefore, simple main effects were run to further

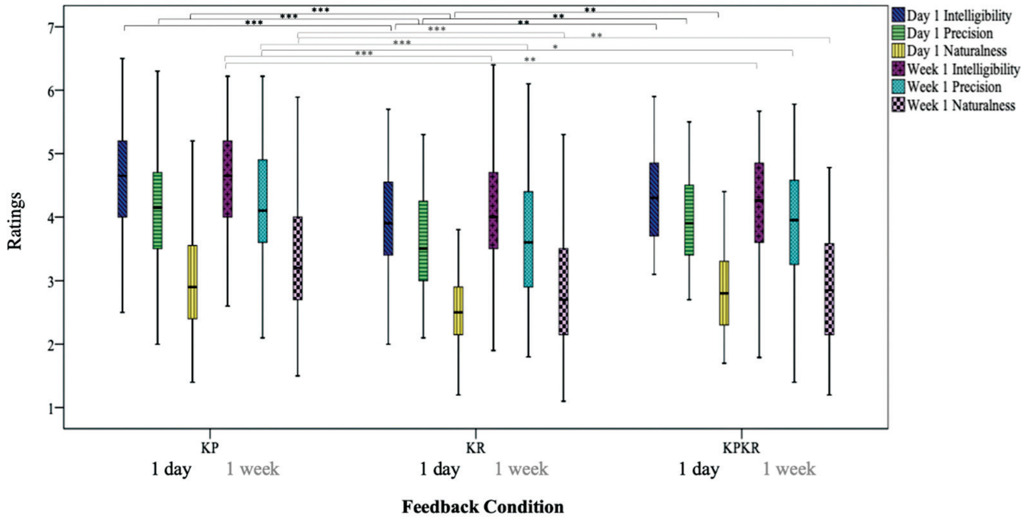

Figure 2 Listener ratings for 1 day and 1 week post-training across feedback type. $^{*}p < 0.05$, $^{**}p < 0.005$, $^{***}p < 0.0005$.

examine effects of feedback type on listener ratings at 1 day and 1 week post-training.

One day post-training. Statistically significant differences in mean intelligibility ratings were found for feedback type at 1 day post-training, $F(1.835, 144.943) = 15.946$, $p < 0.0005$. Post hoc analysis with a Bonferroni adjustment revealed that intelligibility ratings were statistically significantly higher for KP compared to KR (0.630 [95% CI, 0.318–0.942], $p < 0.0005$) and KP + KR compared to KR (0.413 [95% CI, 0.138–0.687], $p = 0.001$), but not KP compared to KP + KR (0.218 [95% CI, −0.22 to 0.457], $p = 0.088$).

One week post-training. Statistically significant differences in mean intelligibility ratings were found for feedback type at 1 week post-training, $F(1.298, 11.663) = 26.94, p < 0.0005$. Post hoc analysis with a Bonferroni adjustment revealed that intelligibility ratings were statistically significantly higher for KP compared to KR (0.616 [95% CI, 0.356–0.876], $p < 0.0005$) and KP compared to KP + KR (0.448 [95% CI, 0.166–0.730], $p = 0.001$), but not KP + KR compared to KR (0.168 [95% CI, −0.0910 to 0.427], $p = 0.348$).

Timepoint. Finally, statistically significant differences in mean intelligibility ratings were found for time for the KP + KR condition only, $F(1, 79) = 68.35$, $p = 0.011$. Mean intelligibility ratings were 0.188 (95% CI, 0.45–0.332) higher at 1 day compared to 1 week post-training. For the KR condition, mean intelligibility ratings were 0.056 (95% CI, −0.209 to 0.096) lower at 1 day post-training as opposed to 1 week post-training, a difference that was not statistically significant, $F(1, 79) = 0.541$, $p = 0.464$. For the KP condition, mean intelligibility ratings were 0.042 (95% CI, −0.191 to 0.06) lower at 1 day post-training as opposed to 1 week post-training, a difference that was not statistically significant, $F(1, 79) = 0.320$, $p = 0.573$.

PRECISION

A two-way repeated measures ANOVA was run to determine the effect of different feedback conditions on listener ratings of precision at two timepoints. Analysis of the studentized residuals showed that there was normality for all conditions at both timepoints ($p > 0.05$) except for the KP condition at 1 week post-training ($p = 0.013$), as assessed by the Shapiro–Wilk test of normality. There were no outliers for all feedback conditions at both timepoints, as assessed by no studentized residuals greater than ± 3 SDs. The assumption of sphericity was met, as assessed by Mauchly's test of sphericity, $\chi^2(2) = 4.235$, $p = 0.120$. There was a statistically significant interaction between feedback type and time on listener ratings of precision, $F(2, 158) = 3.658$, $p = 0.028$. Therefore, simple main effects were run to further examine effects of feedback type on listener ratings at 1 day and 1 week post-training.

One day post-training. Statistically significant differences in mean precision ratings were found for feedback type at 1 day post-training, $F(1.826, 144.255) = 10.834$, $p < 0.0005$. Post hoc analysis with a Bonferroni adjustment revealed that listener ratings of precision were statistically significantly higher for KP compared to KR (0.539 [95% CI, 0.206–0.872], $p < 0.0005$) and KP + KR compared to KR (0.383 [95% CI, 0.111–0.654], $p = 0.003$), but not KP compared to KP + KR (0.156 [95% CI, −0.108 to 0.420], $p = 0.465$).

One week. Statistically significant differences in mean precision ratings were found for feedback type at 1 week post-training, $F(2, 158) = 12.459$, $p < 0.0005$. Post hoc analysis with a Bonferroni adjustment revealed that ratings of precision were statistically significantly higher for KP compared to KR (0.592 [95% CI, 0.301–0.883], $p < 0.0005$) and KP compared to KP + KR (0.384 [95% CI, 0.060–0.708], $p = 0.014$), but not KP + KR compared to KR (0.208 [95% CI, −0.057 to 0.473], $p = 0.177$).

Timepoint. Finally, there were no statistically significant differences in mean precision ratings at 1 day post-training opposed to 1 week post-training for all feedback conditions. For the KR condition, mean precision ratings were 0.044 (95% CI, −0.197 to 0.109) lower at 1 day post-training as opposed to 1 week post-training, $F(1, 79) = 0.324$, $p = 0.571$. For the KP condition, mean precision ratings were 0.097 (95% CI, −0.244 to 0.050) lower at 1 day post-training as opposed to 1 week post-training, $F(1, 79) = 0.374$, $p = 0.573$. For the KP + KR condition, mean precision ratings were 0.131 (95% CI, −0.011 to 0.273) higher at 1 day post-training as opposed to 1 week post-training, $F(1, 79) = 0.688$, $p = 0.069$.

NATURALNESS

A two-way repeated measures ANOVA was run to determine the effect of different feedback conditions on listener ratings of naturalness at two timepoints. Analysis of the studentized residuals showed that there was normality for all conditions at both timepoints ($p > 0.05$) except for the KP condition at 1 week post-training ($p = 0.008$), as assessed by the Shapiro–Wilk test of normality. There were no outliers for all feedback conditions at both timepoints, as assessed by no studentized residuals greater than ± 3 SDs. The assumption of sphericity was violated, as assessed by Mauchly's test of sphericity, $\chi^2(2) = 23.025$, $p = 0.0005$. Therefore, the Greenhouse–Geisser correction was applied ($\epsilon = 0.796$). There was a statistically significant interaction between feedback type and time on listener ratings of naturalness, $F(1.593, 125.835) = 18.546$, $p = 0.0005$. Therefore, simple main effects were run to further examine effects of feedback type on listener ratings at 1 day and 1 week post-training.

One day. Statistically significant differences in mean naturalness ratings were found for feedback type at 1 day post-training, $F(2, 158) = 13.181$, $p = 0.0005$. Post hoc analysis with a Bonferroni adjustment revealed that listener ratings of naturalness were statistically significantly higher for KP compared to KR (0.511 [95% CI, 0.239–0.783], $p < 0.0005$) and KP + KR compared to KR (0.324 [95% CI, 0.104–0.544], $p = .002$), but not KP compared to KP + KR (0.188 [95% CI, −0.057 to 0.432], $p = 0.194$).

One week. Statistically significant differences in mean naturalness ratings were found for feedback type at 1 week post-training, $F(2, 158) = 13.502$, $p < 0.0005$. Post hoc analysis with a Bonferroni adjustment revealed that ratings of precision were statistically significantly higher for KP compared to KR (0.557 [95% CI, 0.272–0.842], $p < 0.0005$) and KP compared to KP + KR (0.482 [95% CI, 0.169–0.794], $p = 0.001$), but not KP + KR compared to KR (0.075 [95% CI, −0.177 to 0.327], $p = 1.000$).

Timepoint. Finally, statistically significant differences in mean naturalness ratings for time were found for the KR and KP conditions. For the KR condition, mean naturalness ratings were 0.280 (95% CI, −0.429 to −0.131) lower at 1 day compared to 1 week post-training, $F(1, 79) = 13.986$, $p = 0.0005$. For the KP condition, mean naturalness ratings were 0.325 (95% CI, −0.460 to 0.191) lower at 1 day post-training as opposed to 1 week post-training, $F(1, 79) = 23.194, p = 0.0005$. For the KP + KR condition, mean naturalness ratings were 0.031 (95% CI, −0.176 to −0.113) lower at 1-day post-training as opposed to 1-week post-training, a difference that was not statistically significant, $F(1, 79) = 0.187, p = 0.667$.

DISCUSSION

This pilot study sought to examine the effect of three feedback conditions on novel speech learning in neurologically healthy adults, as measured by listener ratings of intelligibility, precision, and naturalness at 1 day and 1 week post-training. This work serves as a foundation for future investigations with larger and more diverse samples of participants that vary in age and neurological diagnosis, to further investigate the benefits of feedback type during speech learning. In general, the results of this investigation suggest the type of feedback provided during a 1-hour training session for a novel speech task (Hindi phrases) may influence listener ratings of intelligibility, precision, and naturalness at 1 day and 1 week post-training. On average, listener ratings were highest across all three perceptual scales and at both timepoints for the group that received KP feedback, whereas listener ratings were lowest for the group that received KR feedback. Relative to listener ratings for the KP group, listener ratings for the KP + KR group were more variable across timepoint. These findings are discussed in more depth later.

Influence of Feedback Type on Listener Ratings

One day post–speech training. Listener ratings at 1 day post-training suggest that KP and KP + KP feedbacks are superior to KR feedback in promoting intelligibility, precision, and naturalness of trained speech skills in college-aged neurologically healthy adults when learning a novel speech task. Listener ratings for individuals in the KP condition were, on average, higher than those for individuals in the KP + KR condition. These results are partially consistent with our hypothesis which predicted that the combined feedback condition would enhance performance compared to the other conditions. These findings may suggest that KP is an essential component in training complex novel speech tasks to young healthy adults, especially in the earlier stages of learning. As discussed previously, the nature of the task may impact the benefit of feedback type. Researchers conducting limb motor learning studies have identified guidelines thought to influence the benefit of one feedback type over another (Magill 2004; Sharma et al. 2016). These guidelines may also apply to speech motor learning (Kaipa 2013; Maas et al. 2008). In the current study, the task required specified movement characteristics (e.g., production of new patterns of resonance with new and known articulatory postures) and complex coordination of the articulators and subsystems involved in speech production. According to the guidelines, these specified and complex task characteristics warrant KP over KR (Sharma et al. 2016). Furthermore, KP has proven to be superior to KR when the goal of the task is unknown (Newell et al. 1990). In this study, learners did not have a reliable internal representation of the movement goal because the task was novel, and, therefore, could not use KR to compare with their own intrinsic feedback or determine the outcome of their performance independently.

The results of this study differ from that of Ballard and colleagues (2012) which showed greater benefit of KR feedback compared to a combined KR and KP approach. The current study differs from Ballard and colleagues (2012) in several ways, including a sequential versus simultaneous KP + KR feedback, low (20%) versus high (100%) feedback frequency, biofeedback versus clinician delivered feedback, and differing levels of task complexity (Hindi phrases vs. trilled Russian /r/). In the current study, we were specifically interested in examining each type of feedback on its own (KP only and KR only) and a combined condition thought to be more reflective of clinical care (sequential delivery, first KP and then KR). We chose to incorporate low-frequency feedback as lower rates of feedback have been shown to facilitate learning relative to higher rates of feedback (Maas et al. 2008; Schmidt & Lee 2005). Additionally, there is evidence to suggest that high-frequency feedback may negatively impact the benefits of feedback type (Wulf et al. 2002). The type of KP feedback also differed between the two studies, with the current study providing clinician-delivered KP feedback with verbal instruction and pictures of the articulators, and the study by Ballard and colleagues (2012) using biofeedback via electropalatography. While clinician-delivered feedback can address speech errors or the inaccurate movements of the articulators (e.g., "your lips need to come together to make that sound"), tongue positions and movements, which are not highly visible, can be challenging to verbally cue and describe. Therefore, KP in the form of visual feedback of one's own tongue positions and movements has the potential to bolster motor learning (Preston et al. 2013). Finally, the training task employed in this study was complex and may have driven the need for KP feedback, rather than KR. In contrast, the training task in the study of Ballard et al. (2012) was relatively less complex, and likely did not require the same level of detailed instruction to promote learning. The combination of task complexity, frequency of feedback, and type of KP in the study of Ballard et al. (2012) may have negatively impacted learning. Biofeedback may be more appropriate when training complex tasks; however, research is needed to better understand when biofeedback may be optimal to clinician-delivered feedback to promote speech learning.

One-week post–speech training. Listener ratings at 1 week post-training indicate that KP feedback remained superior to KP + KR and KR feedback in promoting intelligibility, precision, and intelligibility of a novel speech task. These findings support the idea that the benefit of feedback type is determined by the nature of the task, and further suggest that low-frequency KP feedback may be superior to other feedback types when the task is complex and the training phase is short. In the current study, the novelty and complexity of the task coupled with the short training phase most likely enforced a reliance on more detailed feedback. Future work should examine the benefit of feedback type when implementing a performance criterion (e.g., training to 80% accuracy).

Timepoint

The results of time of testing show a similar pattern of benefit of feedback condition across the two timepoints. On average, however, ratings of intelligibility and precision increased from 1-day to 1-week testing for both the KP and KR conditions but were significant only for the naturalness measure. The motor learning literature suggests that consolidation of trained skills occurs during periods of rest (Robertson et al. 2004; Schmidt & Lee 2005). Thus, the slight increase in listener ratings may indicate improvements in aspects of nonnative speakers' speech abilities from 1-day to 1-week testing. In the KP + KR feedback condition, a statistically significant difference was found for listener ratings of intelligibility. In contrast to the other two groups, ratings were higher at 1 day post-training compared to 1 week for the combined feedback group. A similar pattern was observed for listener ratings of precision; however, this finding was not statistically significant. Overall, the pattern of results for the KP + KR feedback condition differed from the KP and KR feedback conditions and do not support the hypothesis that KP + KR would enhance learning at 1 week post-training. As mentioned earlier, the results of the KP + KR condition may indicate that more of only one type of training was needed during the short training phase.

Considerations for MSDs. While this study included neurologically healthy adults without MSDs, this work may have implications for clinical practice with individuals with MSDs. Our findings suggest that KP is an important initial step in training a novel speech task; this may also suggest that KP is an important initial step in the speech rehabilitation process, especially if the speech impairment results from damage to the motor plans for speech production (e.g., acquired AOS; Van der Merwe 2009) and/or impaired auditory or perceptual feedback (e.g., hypokinetic dysarthria; Mollaei et al. 2016). Furthermore, KP may be an important component in speech learning in children with developmental MSDs, such as childhood AOS or dysarthria resulting from cerebral palsy. For example, McKechnie and colleagues (2020) found that a group of speakers with CAS who received KP showed a significant change from pre- to immediately post-treatment compared to those who received KR; however, the group differences dissipated by 1-month post-treatment. Regarding task complexity, our findings may suggest that adults and children with MSDs rely on KP more frequently or for a longer period if the speech task is complex (e.g., multisyllabic words with clusters or phrase production) compared to more simplified tasks (e.g., syllable production). Similarly, persons with MSDs with more severe deficits may also rely on KP for a longer period (prior to moving on to KR) than those with milder deficits. Continued research is needed to better understand the benefit of PML on treatment outcomes for persons with MSDs and the impact of individual (e.g., severity) and task (e.g., complexity) on the application of each PML.

Study Limitations

This study aimed to better understand the impact of feedback type on learning speech skills with hopes to provide guidance for clinical practice. While the findings of this investigation are informative, there are limitations that minimize the application to current clinical practice. First and foremost, the lack of a baseline measure provided by native listeners is a significant limitation to this study. Future work will address this issue by recording participant responses prior to training and then, asking native listeners to rate performance. This will allow for a direct comparison of listener ratings of participant performance pre- and post-training. It is important to note, however, that the training data show similar baseline performance across all three feedback groups. Although the length of the training phase and timing of testing in the current study match previous investigations examining the PML, the expansion of these variables would greatly enhance the clinical applicability of these findings for speech (re) learning in individuals with MSDs, such as AOS, as well as neurologically healthy individuals with articulation difficulties. More specifically, the short training phase (i.e., small amount of practice) coupled with the novelty and complexity of the task may have influenced the benefit of feedback type. Lengthening the training phase and/or training to a specified criterion would better mirror clinical practice. Additionally, extending testing to weeks and/or months post-training will provide insight into the long-term maintenance and generalization effects of feedback type on speech motor learning. Another limitation to the study includes the length of the rating protocol for the expert raters. To avoid listener fatigue and encourage a break after rating half of the audio recordings, the data were presented to listeners via two separate Qualtrics surveys. The presentation of the data in two separate surveys appeared to invite some raters to complete ratings for only one of the two data sets. As a result, some listeners completed more ratings than others with four native listeners rating both data sets (480 items) and 16 native listeners rating one data set (240 items); however, data were randomized and all raters were blind to the testing timepoints (e.g., 1 day and 1 week). Finally, this study did not examine intelligibility, precision, and naturalness during the training phase, only at 1 day and 1 week post–speech training. While we have data to support learning during the training phase, intelligibility, precision, and naturalness were not specifically addressed since the aim of this project was on post-training speech perception. Future work might focus on pre- and post-training comparisons to capture the degree and rate of change over a longer period.

CONCLUSIONS AND FUTURE DIRECTIONS

There is much to learn about the application of motor learning theory to speech motor learning and management of acquired and developmental MSDs. While some literature supports the implementation of the PML into treatment protocols, the evidence is mixed and warrants further investigation. In particular, understanding the type and/or combination of feedback required to optimize treatment outcomes is valuable to everyday therapeutic activities.

The results of this investigation suggest that KP feedback may be superior to KR and KP + KR for enhancing speech production of a novel and complex speech task during a short training phase, as measured by listener ratings. Future studies, however, should further examine the impact of task complexity on feedback type (e.g., Do more complex speech tasks require more detailed feedback compared to simpler tasks?) and the relationship between practice amount and the feedback type (e.g., Is KP feedback superior to KR feedback when the practice amount is small vs. large?). Finally, additional research should also explore training to a specified criterion (e.g., 80% accuracy), as this approach is more applicable to clinical practice.

CONFLICT OF INTEREST

None declared.

ACKNOWLEDGEMENTS

The authors would first like to thank the participants and raters for giving their time and participating in this study. The authors also thank Taylor Walker (research assistant) for her time, great attention to detail, and dedication to this project.

DISCLOSURE

L.B. and E.B.M. received salary for conducting this and other research and have declared that no other competing interests existed at the time of publication. A.T. received salary while completing a portion of this project and has declared that no other competing interests existed at the time of publication.

REFERENCES

Adams, S. G., & Page, A. (2000). Effects of selected practice and feedback variables on speech motor learning. Journal of Medical Speech-Language Pathology, 8, 215–220

Adams, S. G., Page, A. D., & Jog, M. (2002). Summary feedback schedules and speech motor learning in Parkinson's disease. Journal of Medical Speech-Language Pathology, 10(4), 215–220

Anderson, D. I., Magill, R. A., & Sekiya, H. (2001). Motor learning as a function of KR schedule and characteristics of task-intrinsic feedback. Journal of Motor Behavior, 33, 59–66

Austermann Hula, S. N., Robin, D. A., Maas, E., Ballard, K. J., & Schmidt, R. A. (2008). Effects of feedback frequency and timing on acquisition, retention, and transfer of speech skills in acquired apraxia of speech. Journal of Speech, Language, and Hearing Research: JSLHR, 51, 1088–1113

Baddeley, A. D., & Longman, D. J. A. (1978). Influence of length and frequency of training session on rate of learning to type. Ergonomics, 21(8), 627–635

Ballard, K. J., Granier, J. P., & Robin, Donald A. (2000). Understanding the nature of apraxia of speech: theory, analysis, and treatment. Aphasiology, 14(10), 969–995

Ballard, K. J., Maas, E., & Robin, D. A. (2007). Treating control of voicing in apraxia of speech with variable practice. Aphasiology, 21(12), 1195–1217

Ballard, K. J., Smith, H. D., Paramatmuni, D., McCabe, P., Theodoros, D. G., & Murdoch, B. E. (2012). Amount of kinematic feedback affects learning of speech motor skills. Motor Control, 16(1), 106–119

Ballard, K. J., Wambaugh, J. L., Duffy, J. R., Layfield, C., Maas, E., Mauszycki, S., & McNeil, M. R. (2015). Treatment for acquired apraxia of speech: a systematic review of intervention research between 2004 and 2012. American Journal of Speech-Language Pathology, 24(2), 316–337

Bislick, L. (2020). A phonomotor approach to apraxia of speech treatment. Journal of American Speech-Language Pathology, 29, 2109–2130

Bislick, L. P., Oelke, M., & Kendall, D. (2014). Phonomotor rehabilitation of apraxia of speech. Journal of Medical Speech-Language Pathology, 21(1), 15–31

Bislick, L. P., Weir, P. C., Spencer, K., Kendall, D., & Yorkston, K. M. (2012). Do principles of motor learning enhance retention and transfer of speech skills? A systematic review. Aphasiology, 26(5), 709–728

Bislick, L. P., Weir, P. C., & Spencer, K. A. (2013). Investigation of feedback schedules on motor learning in individuals with apraxia of speech. Journal of Medical Speech-Language Pathology, 20(4), 18–23

Clark, H. M., & Robin, D. A. (1998). Generalized motor programme and parameterization accuracy in apraxia of speech and conduction aphasia. Aphasiology, 12, 7–8, 699–713

Croce, R., Horvat, M., & Roswal, G. (1996). Augmented feedback for enhanced skill acquisition in individuals with traumatic brain injury. Perceptual and Motor Skills, 82(2), 507–514

Cullen, K. E., & Mitchell, D. E. (2017). Memory Systems in Learning and Memory: A Comprehensive Reference (J. H. Bryne, ed.). Academic Press

Duffy, J. R. (2013). Motor Speech Disorders: Substrates, Differential Diagnosis, and Management (3rd ed.). Mosby

Gibbons, J. D., & Chakraborti, S. (2011). Nonparametric Statistical Inference (5th ed.). Boca Raton, FL: Chapman & Hall/CRC

Grimme, B., Fuchs, S., Perrier, P., & Schöner, G. (2011). Limb versus speech motor control: a conceptual review. Motor Control, 15(1), 5–33

Hemayattalab, R., & Rostami, L. R. (2010). Effects of frequency of feedback on the learning of motor skill in individuals with cerebral palsy. Research in Developmental Disabilities, 31(1), 212–217

Jones, K., & Croot, K. (2016). The effect of blocked, random and mixed practice schedules on speech motor learning of tongue twisters in unimpaired speakers. Motor Control, 20(4), 350–379

Jonsdottir, J., Cattaneo, D., Recalcati, M., Regola, A., Rabuffetti, M., Ferrarin, M., & Casiraghi, A. (2010). Task-oriented biofeedback to improve gait in individuals with chronic stroke: motor learning approach. Neurorehabilitation and Neural Repair, 24(5), 478–485

Kaipa, R. (2013). Evaluation of principles of motor learning in speech and non-speech-motor learning tasks. [Doctoral dissertation, published online]. University of Canterbury. Accessed February 10, 2023 at: http://hdl.handle.net/10092/10349

Kaipa, R., Robb, M., & Jones, R. (2017). The effectiveness of constant, variable, random, and blocked practice in speech-motor learning. Journal of Motor Learning and Development, 5(1), 103–125

Katz, W. F., McNeil, M. R., & Garst, D. M. (2010). Treating apraxia of speech (AOS) with EMA-supplied visual augmented feedback. Aphasiology, 24(6–8), 826–837

Keele, S. W. (1968). Movement control in skilled motor performance. Psychological Bulletin, 70, 387–403

Kim, I. S., Lapointe, L. L., & Stierwalt, J. A. (2012). The effect of feedback and practice on the acquisition of novel speech behaviors. American Journal of Speech-Language Pathology, 21, 89–100

Knock, T. R., Ballard, K. J., Robin, D. A., & Schmidt, R. A. (2000). Influence of order of stimulus presentation on speech motor learning: a principled approach to treatment for apraxia of speech. Aphasiology, 14(5–6), 653–668

Laerd Statistics. (2016). Kendall's coefficient of concordance, W, using SPSS Statistics. Statistical tutorials and software guides. Accessed February 10, 2023 at: https://statistics.laerd.com/

Lauber, B., & Keller, M. (2014). Improving motor performance: Selected aspects of augmented feedback in exercise and health. European Journal of Sport Science, 14(1), 36–43

Leddy, M. (1999). The biological bases of speech in people with Down syndrome. In: Miller J, Leddy M, & Leavitt LA, (eds), Improving the Communication of People with Down Syndrome (pp. 61–80). Baltimore, MD: Paul H Brookes Publishing

Levin, M. F., & Demers, M. (2021). Motor learning in neurological rehabilitation. Disability and Rehabilitation, 43(24), 3445–3453

Lisman, A. L., & Sadagopan, N. (2013). Focus of attention and speech motor performance. Journal of Communication Disorders, 46(3), 281–293

Lowe, M. S., & Buchwald, A. (2017). The impact of feedback frequency on performance of a novel speech motor learning task. Journal of Speech, Language, and Hearing Research: JSLHR, 60, 1712–1725

Lubold, N., Borrie, S. A., Barrett, T. S., Willi, M., & Berisha, V. (2019). Do conversational partners entrain on articulatory precision? Interspeech, 2019, 1931–1935

Maas, E., Robin, D. A., Austermann Hula, S. N., Freedman, S. E., Wulf, G., Ballard, K. J., & Schmidt, R. A. (2008). Principles of motor learning in treatment of motor speech disorders. American Journal of Speech-Language Pathology, 17, 277–298

Magill, R. A. (2004). Motor Learning and Control: Concepts and Applications (7th edn.). New York: McGraw-Hill

Maier, M., Ballester, B. R., & Verschure, P. F. M. J. (2019). Principles of neurorehabilitation after stroke based on motor learning and brain plasticity mechanisms. Frontiers in Systems Neuroscience, 13, 74

McKechnie, J., Ahmed, B., Gutierrez-Osuna, R., Murray, E., McCabe, P., & Ballard, K. J. (2020). The influence of type of feedback during tablet-based delivery of intensive treatment for childhood apraxia of speech. Journal of Communication Disorders, 87, 106026

Molier, B. I., Van Asseldonk, E. H. F., Hermens, H. J., & Jannink, M. J. A. (2010). Nature, timing, frequency and type of augmented feedback; does it influence motor relearning of the hemiparetic arm after stroke? A systematic review. Disability and Rehabilitation, 32, 1799–1809

Mollaei, F., Shiller, D. M., Baum, S. R., & Gracco, V. L. (2016). Sensorimotor control of vocal pitch and formant frequencies in Parkinson's disease. Brain Research, 1646, 269–277

Nasreddine, Z. S., Phillips, N. A., Bédirian, V., Charbonneau, S., Whitehead, V., Collin, I., Cummings, J. L., & Chertkow, H. (2005). The Montreal Cognitive Assessment, MoCA: a brief screening tool for mild cognitive impairment. Journal of the American Geriatrics Society, 53(4), 695–699

Newell, K. M., Carlton, M. J., & Antoniou, A. (1990). The interaction of criterion and feedback information in learning a drawing task. Journal of Motor Behavior, 22, 536–552

Newell, K. M., & Carlton, M. J. (1987). Augmented information and the acquisition of isometric tasks. Journal of Motor Behavior, 19, 4–12

Newell, K. M., Quinn, J. T., & Carlton, M. J. (1987). Kinematic information feedback and task constraints. Applied Cognitive Psychology, 1, 273283

Newell, K. M., Quinn, J. T., Sparrow, W. A., & Walter, C. B. (1983). Kinematic information feedback for learning a rapid arm movement. Human Movement Science, 2, 255–270

Nunes, M. E. S., Souza, M. G. T. X., Basso, L., Monteiro, C. B. M., Corrêa, U. C., & Santos, S. (2014). Frequency of provision of knowledge of performance on skill acquisition in older persons. Frontiers in Psychology, 5, 1454

Onla-or, S., & Winstein, C. J. (2008). Determining the optimal challenge point for motor skill learning in adults with moderately severe Parkinson's disease. Neurorehabilitation and Neural Repair, 22(4), 385–395

Park, J. H., & Shea, C. H. (2003). Effect of practice on effector independence. Journal of Motor Behavior, 35(1), 33–40

Park, J. H., & Shea, C. H. (2005). Sequence learning: response structure and effector transfer. The Quarterly Journal of Experimental Psychology. A, Human Experimental Psychology, 58(3), 387–419

Preston, J. L., Brick, N., & Landi, N. (2013). Ultrasound biofeedback treatment for persisting childhood apraxia of speech. American Journal of Speech-Language Pathology, 22(4), 627–643

Rice, M. S., & Hernandez, H. G. (2006). Frequency of knowledge of results and motor learning in persons with developmental delay. Occupational Therapy International, 13(1), 35–48

Rice, M. S., Fertig, P. A., Maitra, K. K., & Miller, B. K. (2008). Reduced feedback: motor learning strategy in persons with Alzheimer's disease. Physical & Occupational Therapy in Geriatrics, 27(2), 122–138

Robertson, E. M., Pascual-Leone, A., & Miall, R. C. (2004). Current concepts in procedural consolidation. Nature Reviews. Neuroscience, 5, 576–582

Ronsse, R., Puttemans, V., Coxon, J. P., Goble, D. J., Wagemans, J., Wenderoth, N., & Swinnen, S. P. (2011). Motor learning with augmented feedback: modality-dependent behavioral and neural consequences. Cerebral Cortex (New York, N.Y.), 21, 1283–1294

Saemi, E., Porter, J. M., Ghotbi-Varzaneh, A., Zarghami, M., & Maleki, F. (2012). Knowledge of results after relatively good trials enhances self-efficacy and motor learning. Psychology of Sport and Exercise, 13(4), 378–382

Samudravijaya, K., Rao, P. V. S., & Agrawal, S. S. (2000). Hindi speech database. In: Sixth International Conference on Spoken Language Processing Beijing, China

Sasisekaran, J., Smith, A., Sadagopan, N., & Weber-Fox, C. (2010). Nonword repetition in children and adults: effects on movement coordination. Developmental Science, 13(3), 521–532

Scheiner, L. R., Sadagopan, N., & Sherwood, D. E. (2014). Effects of blocked versus random practice on speech motor skill acquisition and retention. Journal of Motor Learning and Development, 2(2), 29–36

Schmidt, R. A. (2003). Motor schema theory after 27 years: reflections and implications for a new theory. Research Quarterly for Exercise and Sport, 74(4), 366–375

Schmidt, R. A. (1975). A schema theory of discrete motor skill learning. Psychological Review, 82(4), 225–260

Schmidt, R. A. (1988). Motor Control and Learning. Champaign, IL: Human Kinetics

Schmidt, R. A., & Lee, T. D. (2011). Motor Control and Learning: Behavioral Emphasis. Champaign, IL: Human Kinetics

Schmidt, R. A., & Bjork, R. A. (1992). New conceptualizations of practice: common principles in three paradigms suggest new concepts for training. Psychological Science, 3(4), 207–217.

Schmidt, R. A., Lee, T. D., Winstein, C. J., Wulf, G., & Zelaznik, H. N. (2019). Motor Control and Learning: A Behavioral Emphasis. Champaign, IL: Human Kinetics.

Schmidt, R. A., & Lee, T. D. (2005). Motor Control and Learning: A Behavioral Emphasis. Champaign, IL: Human Kinetics

Sharma, D. A., Chevidikunnan, M. F., Khan, F. R., & Gaowgzeh, R. A. (2016). Effectiveness of knowledge of result and knowledge of performance in the learning of a skilled motor activity by healthy young adults. Journal of Physical Therapy Science, 28(5), 1482–1486

Shea, C. H., Lai, Q., Black, C., & Park, J. H. (2000). Spacing practice sessions across days benefits the learning of motor skills. Human Movement Science, 19(5), 737–760

Sidaway, B., Bates, J., Occhiogrosso, B., Schlagenhaufer, J., & Wilkes, D. (2012). Interaction of feedback frequency and task difficulty in children's motor skill learning. Physical Therapy, 92(7), 948–957

Spencer, K. A., & Rogers, M. A. (2005). Speech motor programming in hypokinetic and ataxic dysarthria. Brain and Language, 94(3), 347–366

Spielman, J., Ramig, L. O., Mahler, L., Halpern, A., & Gavin, W. J. (2007). Effects of an extended version of the Lee Silverman voice treatment on voice and speech in Parkinson's disease. American Journal of Speech-Language Pathology, 16(2), 95–107

Steinhauer, K., & Grayhack, J. P. (2000). The role of knowledge of results in performance and learning of a voice motor task. Journal of Voice, 14(2), 137–145.

Van der Merwe, A. (2009). A theoretical framework for the characterization of pathological speech sensorimotor control. In: M. R. McNeil (ed.), Clinical Management of Sensorimotor Speech Disorders (2nd ed.). Thieme

Van der Merwe, A. (2011). A speech motor learning approach to treating apraxia of speech: rationale and effects of intervention with an adult with acquired apraxia of speech. Aphasiology, 25(10), 1174–1206

van Vliet, P. M., & Wulf, G. (2006). Extrinsic feedback for motor learning after stroke: What is the evidence? Disability and Rehabilitation, 28(13-14), 831–840

Varley, R., Whiteside, S., Windsor, F., & Fisher, H. (2006). Moving up from the segment: a comment on Aichert and Ziegler's syllable frequency and syllable structure in apraxia of speech, brain and language, 88, 148-159, 2004. Brain and Language, 96, 235–239

Wambaugh, J. L., Nessler, C., Cameron, R., & Mauszycki, S. C. (2013). Treatment for acquired apraxia of speech: examination of treatment intensity and practice schedule. American Journal of Speech-Language Pathology, 22(1), 84–102

Wambaugh, J. L., Nessler, C., Wright, S., & Mauszycki, S. C. (2014). Sound production treatment: Effects of blocked and random practice. American Journal of Speech-Language Pathology, 23(2), S225–S245

Weir-Mayta, P., Hamilton, A., Stockton, J. D., & Munoz, C. (2022). Feedback schedule effects on speech motor learning in older adults. Physical Activity and Health, 6(1), 228–245

Weir-Mayta, P., Spencer, K. A., Daliri, A., Bierer, S., & Ondish, P. (2019). Feedback schedule effects on speech motor learning in older adults. International Journal of Aging Research, 2, 33

Woldag, H., Stupka, K., & Hummelsheim, H. (2010). Repetitive training of complex hand and arm movements with shaping is beneficial for motor improvement in patients after stroke. Journal of Rehabilitation Medicine, 42, 582–587

Wright, D. L., Black, C. B., Immink, M. A., Brueckner, S., & Magnuson, C. (2004). Long-term motor programming improvements occur via concatenation of movement sequences during random but not during blocked practice. Journal of Motor Behavior, 36(1), 39–50

Wulf, G., & Schmidt, R. A. (1997). Variability of practice and implicit motor learning. Journal of Experimental Psychology. Learning, Memory, and Cognition, 23(4), 987–1006

Wulf, G., McConnel, N., Gärtner, M., & Schwarz, A. (2002). Enhancing the learning of sport skills through external-focus feedback. Journal of Motor Behavior, 34(2), 171–182

Yorkston, K. M., Beukelman, D. R., Strand, E. A., & Bell, K. R. (1999). Management of Motor Speech Disorders in Children and Adults (2nd ed.). Austin, TX: Pro-Ed

Young, D. E., & Schmidt, R. A. (1992). Augmented kinematic feedback for motor learning. Journal of Motor Behavior, 24(3), 261–273