Tutorial

Principles of Motor Learning in Treatment of Motor Speech Disorders

Edwin Maas
University of Arizona, Tucson

Donald A. Robin
University of Texas Health Science Center at San Antonio, and Honors College, University of Texas San Antonio

Shannon N. Austermann Hula
Skott E. Freedman
San Diego State University and University of California, San Diego

Gabriele Wulf
University of Nevada, Las Vegas

Kirrie J. Ballard
University of Iowa, Iowa City, and University of Sydney, Lidcombe, Australia

Richard A. Schmidt
Emeritus, University of California, Los Angeles

Purpose: There has been renewed interest on the part of speech-language pathologists to understand how the motor system learns and determine whether principles of motor learning, derived from studies of nonspeech motor skills, apply to treatment of motor speech disorders. The purpose of this tutorial is to introduce principles that enhance motor learning for non-speech motor skills and to examine the extent to which these principles apply in treatment of motor speech disorders.
Method: This tutorial critically reviews various principles in the context of nonspeech motor learning by reviewing selected literature from the major journals in motor learning. The potential application of these principles to speech motor learning is then discussed by reviewing relevant literature on treatment of speech disorders. Specific attention is paid to how these principles may be incorporated into treatment for motor speech disorders.
Conclusions: Evidence from nonspeech motor learning suggests that various principles may interact with each other and differentially affect diverse aspects of movements. Whereas few studies have directly examined these principles in speech motor (re)learning, available evidence suggests that these principles hold promise for treatment of motor speech disorders. Further research is necessary to determine which principles apply to speech motor (re)learning in impaired populations.

Key Words: motor learning, motor speech disorders, conditions of practice, conditions of feedback

The plasticity of the human brain, even in adults, is clear from animal research (e.g., Nudo, Wise, SiFuentes, & Milliken, 1996) as well as human data (e.g., Liotti et al., 2003; for reviews, see Doyon & Benali, 2005; Rijntjes & Weiller, 2002). Critically for clinicians, behavioral treatments are known to promote brain reorganization and plasticity (e.g., Johansen-Berg et al., 2002; Liotti et al., 2003; Nudo et al., 1996). Understanding how the motor system reorganizes itself based on behavioral intervention can provide important insights into treatment of motor speech disorders (MSDs). This tutorial is designed to fill a void in the literature by critically reviewing principles of motor learning and their potential application to treatment of speech disorders. The focus is on behavioral rather than neural aspects of principles of motor learning, as it is the behavioral implementation that is most directly relevant for clinicians working with clients with MSDs.

MSDs result from a speech production deficit arising from impairment of the motor system (Darley, Aronson, & Brown, 1975; Duffy, 2005). MSDs may be caused by disruption of high-level motor commands, neuromuscular processes, or both. MSDs include both developmental and acquired forms of dysarthria and apraxia of speech (AOS). Dysarthria refers to "a group of speech disorders resulting from disturbances in muscular control" (Darley et al., 1975, p. 2), whereas AOS is considered an impairment of speech motor planning or programming (e.g., Ballard, Granier, & Robin, 2000; Darley et al., 1975; McNeil, Doyle, & Wambaugh, 2000).

Many treatments for MSDs aim to establish new motor routines or reestablish old ones, and thus involve motor learning. Because speech production is a motor skill, the motor-learning literature may provide important insights into how to enhance (re)learning/organization of the speech motor system and, ultimately, the quality of life of individuals with MSDs. Motor skill learning is facilitated by a number of factors pertaining to the structure of practice, stimulus selection, and the nature of feedback, factors that are components of all treatment programs and are thus pertinent to clinical decisions regarding the treatment of any individual client with an MSD. This tutorial aims to (a) detail these factors, referred to as principles of motor learning, and (b) review the extent to which these principles have been or may be applied to speech motor learning, with an emphasis on treatment of MSDs. Throughout the tutorial, gaps in current understanding and directions for further research will be identified.

Before we turn to the principles of motor learning, the following background section first discusses several important caveats and concepts related to motor learning, outlines a theoretical framework that has generated much of the motor-learning research, and relates this framework to speech motor control and MSDs. In the final section of the article, a number of important clinical implications are highlighted and illustrated with a case example.

Background

The principles of motor learning discussed in this tutorial have emerged from studies involving nonspeech motor tasks largely performed by individuals with intact motor systems. Thus, the extension of these principles to treatment of MSDs faces two potential limitations of generality. First, it is unknown whether speech motor control is sensitive to the same principles of learning as nonspeech motor control. A reasonable hypothesis is that speech production, as a motor skill, is governed by similar principles of motor learning. Indeed, others have advocated this approach in articles and textbooks on treatment of MSDs (e.g., Duffy, 2005; McNeil, Robin, & Schmidt, 1997; Robin, Maas, Sandberg, & Schmidt, 2007; Yorkston, Beukelman, Strand, & Bell, 1999). It is consistent with an evidence-based practice philosophy (e.g., American Speech-Language-Hearing Association, 2005) that treatment of MSDs be guided by the best available knowledge about motor skill learning, and that this knowledge base include evidence from nonspeech motor-learning research. Although it is possible that principles of motor learning affect speech and nonspeech motor learning differently, this is an empirical question that warrants further research.

Second, it is unknown whether impaired motor systems are sensitive to the same principles of learning as intact motor systems. Impaired and intact motor systems may respond differently to principles of motor learning. Again, this is an empirical question, and in the absence of evidence to the contrary, principles of motor learning in intact motor systems can provide a framework for our treatment efforts. Supportive evidence from the physical therapy literature suggests that principles of motor learning enhance treatment of neurologically impaired motor systems (e.g., Hanlon, 1996; Landers, Wulf, Wallmann, & Guadagnoli, 2005; Van Vliet & Wulf, 2006; see Krakauer, 2006, for review).

Learning Versus Performance

In the study of motor learning, it is important to consider the distinction between performance during *acquisition* and performance during *retention/transfer*. Following Schmidt and Lee (2005), motor learning refers to "a set of processes associated with practice or experience leading to relatively permanent changes in the capability for movement" (p. 302). This definition implies that learning should be distinguished from temporary performance enhancement, and that learning cannot be directly observed but rather must be inferred from changes in performance over time (cf. Schmidt, 1972).

The distinction between performance during acquisition (practice) and retention/transfer implies that learning, a permanent change in *capability* for skilled movement, must be measured by retention and/or transfer tests. Retention refers to performance levels after the completion of practice. An improved capability for skilled movement should not only be observable during practice but should be retained over time. Transfer (generalization) refers to whether practice on one movement affects related but untrained movements. A change in capability could also be evident as transfer to similar but untrained movements. Measures of retention and/or transfer are critical in research and clinical practice because performance during practice may be affected by factors that do not necessarily reflect learning (e.g., warm-up, fatigue, attentional drift). Failure to distinguish between performance during practice and retention/transfer has resulted in a history of misconceptions about principles of motor learning and their effect on skill learning (Schmidt & Bjork, 1992). However, it is now well established in the motor-learning literature that performance during practice is a poor predictor for retention and transfer. This distinction between practice performance and retention/transfer does not imply that learning processes do not occur during practice. In fact, the differential effects of various practice and feedback conditions applied during the acquisition phase provide insights into how learning occurs. The critical take-home message is that performance changes during practice do not predict retention or transfer, and that testing after practice has stopped is necessary to document the effectiveness of a given practice approach.

The speech-language treatment literature recognizes the performance distinctions noted above in different terms by exploring acquisition (performance during practice), maintenance (retention), and generalization (transfer) in treatment studies. Given that the primary goal of treatment is not to improve performance during the therapy session, per se, but rather to maximize learning (i.e., retention and/or transfer beyond the therapy session), this tutorial will emphasize maintenance and generalization measures over acquisition data.

To facilitate understanding of principles of motor learning, a brief outline of a prominent theory of motor control and learning, namely Schema Theory (Schmidt, 1975, 2003; Schmidt & Lee, 2005), is presented below. Other theories of motor control and learning exist (e.g., dynamical systems theory; Kelso, 1995; Kelso, Saltzman, & Tuller, 1986); however, it is beyond the scope of this tutorial to review and compare the various theories. Schema Theory is used as an organizing framework because it has been instrumental in driving research on motor learning in the nonspeech domain.

A Theory of Motor Control and Learning: Schema Theory

Schema Theory (Schmidt, 1975, 2003; Schmidt & Lee, 2005) assumes that production of rapid discrete movements involves units of action (motor programs) that are retrieved from memory and then adapted to a particular situation. A motor program is an organized set of motor commands that can be specified before movement initiation (Keele, 1968). To account for the fact that movements are never produced exactly the same yet still maintain their essential characteristics, Schema Theory assumes that motor programs are generalized, in that they capture the invariant aspects of the movement. A generalized motor program (GMP) is an abstract movement pattern that specifies relative timing and relative force of muscle contractions, whereas the absolute timing and force (and perhaps the specific effectors or muscles to be used in the movement)[1] are specified by parameters (Schmidt, 1975; Schmidt & Lee, 2005). A general class of movements may be governed by a single GMP, which can be scaled to meet the current task demands. For example, a golf swing involves a basic pattern of a backswing and a forward swing motion (governed by the GMP), but the overall duration and amplitude of that movement, as well as the specific muscles to use (parameters), may depend on the distance that the golf ball must travel.

[1]An effector is a body part or structure that can be used to execute (effect) a movement.

To select the optimal instructions to the musculature and control the body in a wide range of situations, the motor system must know the relations among the initial conditions (e.g., current position of the hands, distance between golf ball and hole), the generated motor commands (e.g., timing and amplitude of arm muscle contractions), the sensory consequences of these motor commands (e.g., proprioception of arm movement, tactile sensation of the club hitting the ball), and the outcome of the movement (e.g., whether the ball ended up in the hole). In Schema Theory, this knowledge is captured in terms of *schemas,* which are memory representations that encode the relations among these types of information, based on past experience with producing similar actions (those involving the same GMP). After each movement with a particular GMP, these types of information are temporarily available in short-term memory and are used to update or create two different schemas, namely the recall schema and the recognition schema. The recall schema encodes the relations among the initial conditions, the parameters that were used to execute the movement, and the outcome of the movement. In order to produce a movement, the system supplies the recall schema with the movement goal (intended outcome) and information about the current conditions, from which the recall schema computes the appropriate parameters.

The recognition schema encodes the relations among the initial conditions, the sensory consequences of the movement, and the outcome of the movement. Given a movement goal and the initial conditions, the recognition schema predicts the sensory consequences that will occur if the movement goal is reached. The recognition schema thus allows the system to evaluate movements by comparing the actual sensory consequences with the expected sensory consequences of a correct movement; a mismatch between the actual and expected consequences represents an error signal that is used to update the recall schema. Before the recognition schema can be used to judge the accuracy of the movement, the system must first learn which sensory consequences are to be considered "correct." There is often a clear reference of correctness (e.g., a golf ball must end up in the hole), but there are cases in which the reference of correctness is not directly available or interpretable to the learner but instead depends on feedback from an instructor, such as when learning to perform a somersault in diving. In such cases, the learner must calibrate the expected sensory consequences with an externally provided reference of correctness, so that the internal error signal may serve to correct errors on future trials without external feedback.

Finally, Schema Theory assumes that a series of GMPs that necessarily occur in a particular serial order (such as speech or typing) may become integrated, or "chunked," into a single, larger GMP with large amounts of practice (Schmidt & Lee, 2005). The notion of chunking is not specific to Schema Theory and is also incorporated into other models of motor programming (e.g., Klapp, 1995; Sakai, Hikosaka, & Nakamura, 2004; see Rhodes, Bullock, Verwey, Averbeck, & Page, 2004, for review).

The notion that motor learning establishes relations among various sources of information allows for several predictions. First, if any of the four types of information is unavailable following a movement, no schema updating (learning) can occur. For example, if a learner does not know whether the produced action was correct (no information about the movement outcome), then the schemas cannot be updated. Second, transfer of learning can occur to other movements based on the same GMP, because learning involves establishing (GMP-specific) schema *rules* that can generate parameterizations even for novel situations (e.g., a different golf club, a different distance from the hole). Third, experience with a wide range of parameter specifications and movement outcomes will increase the stability of a schema rule. Finally, incorrect movements may also provide learning opportunities and allow for development of more precise error detection and correction mechanisms. An incorrect movement produces the same types of information as correct movements, and thus can be used to update the schema.

Speech Motor Control and Learning

Within a Schema Theory perspective, speech production involves GMP and parameter development that encompasses the coordination of all speech production subsystems. However, it remains to be specified which aspects of speech movements are to be considered GMPs and which aspects can be considered parameters (Ballard et al., 2000). A GMP could correspond to the motor commands associated with a phoneme, a syllable, a word, or even a frequently produced phrase (Varley, Whiteside, Windsor, & Fisher, 2006; cf. the notion of chunking above). Factors such as speech rate and degree of clarity might be considered parameters relating to absolute timing and amplitude. The specific muscle group that will execute the movement might also be a parameter. For instance, the syllables "pie" and "tie" might both be governed by the same GMP, differing only in the effector-parameter (labial vs. alveolar). In contrast, the syllables "tie" and "sigh," while sharing the same articulator, might involve different GMPs because they differ in relative movement amplitude (full closure vs. narrow constriction). These suggestions predict transfer across place of articulation (same GMP) but not across manner of articulation (different GMPs), a prediction that finds some support in the AOS treatment literature (e.g., Austermann Hula, Robin, Maas, Ballard, & Schmidt, in press; Ballard, Maas, & Robin, 2007; Wambaugh, Martinez, McNeil, & Rogers, 1999).

Schema Theory appears to provide a viable framework for speech motor programming. Based on the movement goal (e.g., the spoken word "buy" that is audible to a listener) and the current conditions (e.g., ambient noise level, distance from listener, jaw position), the GMP associated with the syllable /baɪ/ is supplied with appropriate parameters (e.g., expiratory muscle force to regulate loudness) based on the established recall schema. The sensory consequences of the movement (e.g., tactile, proprioceptive, auditory information) are evaluated with the recognition schema and compared against the success of the movement (e.g., listener's identification of the word, the speaker's own judgment of an adequate signal). If the listener did not understand the speaker, then a given parameter value must be modified on the next attempt.

It should be noted that several key concepts of Schema Theory (motor programs, schema-type relations) are also incorporated in the recent DIVA model of speech production (e.g., Guenther, 2006; Guenther, Ghosh, & Tourville, 2006; Guenther, Hampson, & Johnson, 1998). Space limitations prevent a detailed exposition of the DIVA model; interested readers are referred to Guenther (2006) and Guenther et al. (1998, 2006) for more details.

MSDs and Speech Motor Learning

Thus far, we have provided a framework for motor control and learning in reference to intact motor systems. However, the extent to which principles of motor learning apply to impaired systems must also be considered. Schema Theory emphasizes motor programming and as such appears particularly applicable to disorders of motor programming (e.g., AOS), though principles of motor learning apply to any situation in which motor learning must take place. AOS may involve a deficit in activating and/or parameterizing GMPs. That is, either the GMP is damaged (e.g., Aichert & Ziegler, 2004; Clark & Robin, 1998), the schema that supplies the parameter settings is impaired (e.g., Clark & Robin, 1998; Kent & Rosenbek, 1983), or both. Alternatively, disturbances in processing somatosensory feedback may disrupt motor programming because information about the initial conditions is unavailable or incorrect (Ballard & Robin, 2007; Kent & Rosenbek, 1983). Damage to the recognition schema may lead to poor error detection (Kent & Rosenbek, 1983), suggesting that augmented (clinician-provided) feedback about accuracy may be especially critical.

The principles of motor learning discussed in this article are also relevant to other MSDs. First, there is evidence that motor programming is disrupted in Parkinson's disease and ataxia (Spencer & Rogers, 2005). Second, damage to downstream motor-control processes—that is, processes subsequent to motor program retrieval and parameterization (e.g., as in flaccid paralysis)—will alter the established relations between the motor commands, sensory consequences, and movement outcomes. Thus, premorbid motor specifications will not produce the intended movement outcomes, nor will the actual sensory consequences match the sensory consequences predicted from the movement goal. As a result, the system must modify the recall and recognition schemas to reflect the new relations to achieve the movement goal. The physical therapy literature provides some evidence for the potential applicability of various principles of motor learning to lower level (noncortical) motor impairments, such as in treating hemiparesis following stroke (e.g., Hanlon, 1996) and balance disturbance in Parkinson's disease (Landers et al., 2005).

As an example of how the theory may apply to MSDs other than AOS, it has been suggested that hypokinetic dysarthria involves a mismatch between perceived vocal effort and perceived loudness, such that these speakers fail to recognize that their speech is hypophonic (e.g., Dromey & Adams, 2000; Fox, Morrison, Ramig, & Sapir, 2002). The expected sensory consequences predicted by the recognition schema would be poorly calibrated with respect to some external reference of correctness (e.g., a certain minimal loudness level in order to be understood). Note that the actual and expected sensory consequences may nonetheless match (these clients may achieve their expected sensory consequences, but these expected consequences are inadequate), so that there will be no error signal that can be used to update the recall schema for future attempts. In this case, clinician-provided feedback would be critical in recalibrating the expected sensory consequences, suggesting that consideration of feedback conditions is important for this population. In addition, the recall schema will need to be updated (e.g., to increase loudness and reduce hypoarticulation), which may benefit from practice conditions that enhance schema learning.

In sum, we hypothesize that principles of motor learning extend to impaired speech motor systems. Optimal conditions of practice and feedback likely depend in part on the nature and severity of the underlying impairment and the presence of concomitant impairments. A recent framework for optimizing learning posits that the extent of learning depends on the amount of information available and interpretable to the learner, which depends on factors such as functional task difficulty (how difficult a task is for a given learner), nominal task difficulty (how difficult the task is, regardless of the learner), and the learner's skill level (Guadagnoli & Lee, 2004). This *challenge point framework* captures the idea that learning can only occur when the learner is challenged, and that learning may be hampered if the challenge is too great or not great enough. The framework suggests that each learner has a challenge point at which availability and interpretability of information are optimal (the optimal challenge point), and that this optimal challenge point depends on task difficulty and the skill level of the learner. Principles of motor learning might affect nominal and functional task difficulty, while skill level may relate to severity of impairment, which might influence the optimal conditions of practice and feedback.

With this background, the remainder of this tutorial discusses several principles of motor learning. Because these principles concern *relative* effects (differences between conditions) rather than each condition's absolute effect, the primary focus is on those studies that have explicitly compared different conditions. The tutorial concludes with a discussion of the clinical implications of the evidence and suggestions for further research.

Principles of Motor Learning

At the outset, we note that this review is not intended to be exhaustive; rather, representative evidence will be summarized. In addition, space limitations prevent discussion of several more recently described factors that may be relevant to treatment for MSDs, such as the effects of an auditory model before the movement (see Lai, Shea, Bruechert, & Little, 2002; C. H. Shea, Wulf, Park, & Gaunt, 2001) or the use of self-controlled feedback (see Chiviacowsky & Wulf, 2005; Janelle, Barba, Frehlich, Tennant, & Cauraugh, 1997).

The principles below are divided into those relating to the structure of practice and those relating to the nature of augmented feedback. Summaries are provided in Table 1 (structure of practice) and Table 2 (nature of feedback). In addition, because the motor-skill-learning literature typically distinguishes between prepractice and practice, we briefly discuss prepractice before discussing practice conditions in more detail.

Prepractice

Prepractice considerations are largely independent of the specific training program that is employed. Prepractice is intended to prepare the learner for the practice session (Schmidt & Lee, 2005). Important goals are to ensure (a) proper motivation to learn, (b) an adequate understanding of the task (including what responses are considered "correct"), and (c) stimulability for acceptable responses (to avoid frustration due to complete inability to produce target).

Motivation may be enhanced by understanding the relevance of the practice task for the overall goal, improved speech. If clients understand that (and how) the treatment activities are designed to increase communication success (e.g., by improving speech intelligibility) and reduce the risk of communication breakdown, they may be more motivated to engage fully in treatment tasks. Selecting functionally relevant treatment targets, and including the client in the target-selection process, can be expected to increase motivation (e.g., Strand & Debertine, 2000). Motivation may also be improved by setting specific goals rather than asking learners to "do the best they can" (McNeil et al., 1997). For example, if the goal is to reduce speech rate in order to improve intelligibility, one could set a specific goal in terms of number of words per minute.

Understanding the task is important for learning. Task instructions should not be too lengthy or complex (especially in the case of co-occurring language disorders); overinstruction should be avoided (Schmidt, 1991). Modeling by the clinician may be useful at this stage, so that the client can see and hear how the target behaviors look and sound. To ensure that the learner understands the task, he or she should be provided with a reference of correctness (information about which productions are acceptable and which ones are not, and why). This information presumably enables the learner to tune internal error-detection mechanisms. With respect to speech in particular, it is important to ensure adequate auditory perception abilities; otherwise, the response evaluation by the client will suffer.

Structure of Practice

Practice Amount: Large Versus Small Amounts of Practice

Practice amount refers to the amount of time spent practicing movements. A large number of practice trials provides more opportunities to establish relationships among the various types of information associated with each movement, and is thereby thought to enhance the stability of recall and recognition schemas. In addition, a large number of trials requires many instances of retrieval of the motor programs, which may automatize the activation of GMPs on future trials.

TABLE 1. Practice conditions.

Condition	Options	Description	Notes	Evidence in speech
Practice amount	Small vs. **large**	Small: low number of practice trials or sessions Large: high number of practice trials or sessions	Potential interaction with practice variability (high number of constant practice trials may be detrimental to learning)	No systematic evidence
Practice distribution	Massed vs. **distributed**	Massed: practice a given number of trials or sessions in small period of time Distributed: practice a given number of trials or sessions over longer period of time		No systematic evidence
Practice variability	Constant vs. **variable**	Constant: practice on the same target, in the same context (e.g., syllable-initial /f/) Variable: practice on different targets, in different contexts (e.g., syllable-initial and final /f/, /z/, /b/)	Potential interactions with practice schedule, amount, complexity, and feedback variables Opposite effects on GMP vs. parameter learning	Limited evidence for benefit of variable practice in unimpaired speech motor learning; no evidence from MSD
Practice schedule	Blocked vs. **random**	Blocked: different targets practiced in separate, successive blocks or treatment phases (e.g., treatment on /f/ before initiating treatment on /z/) Random: different targets practiced intermixed (e.g., practice on /f/ and /z/ in each session)	Potential interactions with practice amount and complexity Opposite effects on GMP vs. parameter learning	Limited evidence for benefit of random practice, in unimpaired speech motor learning and treatment for AOS
Attentional focus	Internal vs. **external**	Internal: focus on bodily movements (e.g., articulatory placement) External: focus on effects of movements (e.g., acoustic signal)	Focus must be task-related Difficult to define external for speech	No systematic evidence
Target complexity	Simple vs. **complex**	Simple: easy, earlier acquired sounds and sound sequences (e.g., plosives, CV-syllables) Complex: difficult, later acquired sounds and sound sequences (e.g., affricates, CCV syllables)	Potential interactions with practice schedule, feedback variables, and learner's skill level	Limited evidence for benefit of targeting complex items in treatment for AOS

Note. Options that may be expected to enhance learning are indicated in bold. GMP = generalized motor program; MSD = motor speech disorder; AOS = apraxia of speech.

TABLE 2. Feedback conditions.

Condition	Options	Description	Notes	Evidence in speech
Feedback type	KP vs. **KR**	KP: knowledge of performance, how a sound was produced (e.g., biofeedback) KR: knowledge of results, whether a sound was correct or incorrect	Potential interactions with learner's error detection abilities	No systematic evidence
Feedback frequency	High vs. **low/summary-KR**	High: feedback after every attempt at production (regardless of accuracy) Low: feedback only after some attempts at production (regardless of accuracy)	Potential interactions with practice variability, attentional focus, complexity, and learner's skill level and error detection abilities Opposite effects on GMP and parameter learning	Some evidence for benefit of reduced feedback frequency in treatment for AOS and speech motor learning in hypokinetic dysarthria
Feedback timing	Immediate vs. **delayed**	Immediate: feedback immediately following attempt at production Delayed: feedback provided with a delay (e.g., 5 s)	Potential interactions with attentional focus	Some evidence for delayed feedback in treatment for AOS and hypokinetic dysarthria

Note. Options that may be expected to enhance learning are indicated in bold.

Nonspeech. There are few studies that specifically compare differential effects of amount of practice; nonetheless, the existing literature generally shows that increasing the amount of practice results in greater retention (e.g., Park & Shea, 2003, 2005; C. H. Shea & Kohl, 1991). However, this principle may interact with other conditions of practice, potentially obscuring its benefit. In particular, there is evidence that, for constant practice (in which the exact same movement is practiced; see the *Practice Variability: Variable Versus Constant Practice* subsection below), a large amount of practice results in poorer retention and/or transfer than a small amount of practice, whereas for variable practice, a large amount of practice produces greater learning than a small amount of practice (e.g., Giuffrida, Shea, & Fairbrother, 2002; C. H. Shea & Kohl, 1991). During constant practice, the motor-program retrieval operations may not be fully engaged on each trial, because the motor program and its parameterization could be kept in a working memory buffer from trial to trial, resulting in impoverished learning (Lee & Magill, 1983, 1985). A larger number of trials in a constant-practice condition may lead to learning highly specific aspects of a task (producing high accuracy during practice) but very limited transfer (generalization).

With small amounts of practice, the learned movement pattern and its scaling are relatively effector-independent (e.g., practice with the left arm transfers to the right arm), whereas a large amount of practice results in greater retention (e.g., for the left arm) at the expense of transfer to another effector (e.g., no additional benefits for the right arm; Park & Shea, 2003, 2005). One interpretation is that with increasing numbers of practice trials, the specific biomechanical properties of the effector used during practice may become integrated in the movement representation (Park & Shea, 2003). Keetch, Schmidt, Lee, and Young (2005) have suggested the possibility that a new GMP develops for the specific highly practiced instance that optimizes all aspects of the task but does not transfer to other, similar movements.

Speech. Although many speech treatment programs recommend a large number of trials (e.g., Chumpelik, 1984; Fox et al., 2002; Rosenbek, Lemme, Ahern, Harris, & Wertz, 1973; Van Riper & Irwin, 1958; Wambaugh, Kalinyak-Fliszar, West, & Doyle, 1998), we found no empirical data bearing on this issue. For example, the Lee Silverman Voice Treatment (LSVT) includes large amounts of practice as an integral component to this efficacious speech treatment for hypokinetic dysarthria (e.g., Fox et al., 2002; Ramig, Countryman, Thompson, & Horii, 1995), but there are no LSVT studies that have compared different amounts of practice systematically. Schulz, Dingwall, and Ludlow (1999) examined speech motor learning in individuals with ataxic dysarthria and failed to find a difference in practice performance with 30 versus 50 practice trials (a small amount of practice in the motor-learning literature). However, the difference in number of trials was relatively small, and this study did not include a retention test that would be critical to address the effects on learning.

In summary, while there are some constraints on the power of large amounts of practice (e.g., under constant practice conditions), in general *a large number of practice trials is beneficial for learning* nonspeech motor skills. No empirical evidence regarding practice amount is available with respect to speech motor learning. (Note that attempts are being made to study this variable in other communication disorders; e.g., see reviews of aphasia treatment by Basso, 2005, and Robey, 1998.)

Practice Distribution: Massed Versus Distributed Practice

Practice distribution refers to how a given (fixed) amount of practice is distributed over time (regardless of whether practice involves a blocked or random schedule; see the *Practice Schedule: Random Versus Blocked Practice* subsection below). Although Schema Theory does not make predictions about practice distribution, this principle is included because evidence suggests that distributed practice (more time between practice trials or sessions) results in greater learning than massed practice (less time between trials or sessions), with important implications for clinical practice. Distribution across several days is encountered frequently in clinical settings, and treatment intensity is often debated at individualized educational plan meetings.

Nonspeech. Practice distribution can be defined in terms of the time between trials or between sessions for the same number of practice trials. The nonspeech evidence strongly suggests that distributing practice over a longer period facilitates both immediate performance and retention for different motor tasks (e.g., Baddeley & Longman, 1978; C. H. Shea, Lai, Black, & Park, 2000; see Lee & Genovese, 1989, for a meta-analysis). Baddeley and Longman (1978) distributed the same amount of practice on a keyboard-entry task over 15 days (massed) or 60 days (distributed), and found that benefits of distributed practice persisted 9 months after training, whereas massed practice gains dissipated shortly after training ended. One possible explanation is that the benefits of distributed practice are due to increased opportunity for memory-consolidation processes (Robertson, Pascual-Leone, & Miall, 2004).

Speech. Few empirical data exist on effects of practice distribution in speech motor learning. With LSVT, which involves relatively massed practice (four treatment sessions per week for 4 weeks; Fox et al., 2002), long-term benefits have been observed (e.g., Ramig, Sapir, Countryman, et al., 2001; Ramig, Sapir, Fox, & Countryman, 2001). Such findings are positive, but distributed practice might have enhanced outcomes even more. A recent study by Spielman, Ramig, Mahler, Halpern, and Gavin (2007) examined the effects of an extended (8-week) LSVT program in 12 individuals with dysarthria secondary to Parkinson's disease. The number and duration of treatment sessions was the same as in the typical 4-week LSVT program, although the extended program involved more homework. Spielman and colleagues observed improvements, including at a 6-month retention test, comparable to those obtained in a previous study using the more traditional 4-week LSVT program (Ramig, Sapir, Fox, & Countryman, 2001). In other words, more distributed practice did not appear to enhance learning relative to more massed practice. Contrary to nonspeech findings, no differences were observed in the amount of learning between traditional and extended LSVT versions. Spielman et al. (2007) noted that the extended LSVT program increases the time commitment for both client and clinician, in particular for unbillable preparation time; this might support the use of the more massed, 4-week LSVT program given that no additional gains were demonstrated for the extended program. Although this study represents an important first step in assessing practice distribution effects in treatment of MSDs, further study is needed to determine the optimal range of practice distribution for various MSDs.

Given current models of treatment and the demands of reimbursement in the current health care climate, this issue requires careful future study. Indeed, outpatient treatments are typically provided two times a week in sessions lasting from 30 to 60 min. In the school environment, the size of caseloads often prohibits more intensive models of treatment. Therefore, if more or less distribution is needed than current practice allows, then a systematic change will be required. The optimal degree of distribution may depend on the specific MSD.

In sum, *distributed practice facilitates both short-term performance and long-term learning* in the nonspeech domain, but this issue requires further study in the speech domain.

Practice Variability: Variable Versus Constant Practice

Constant practice refers to practice on only one variant (parameterization) of a movement (GMP), whereas variable practice targets more than one variant of a given movement (e.g., practicing a golf swing over varying distances from the hole). Experience with a wide range of movement outcomes, initial states, and sensory consequences for a particular GMP should result in a more reliable schema, because practice variability highlights the relations among these types of information for variations of a given task (Schmidt & Bjork, 1992). In turn, a more reliable schema should facilitate transfer to other movements of the same general class, but not to movements that require a different GMP.

Nonspeech. The benefit of variable over constant practice has been confirmed for a variety of tasks (e.g., Lee, Magill, & Weeks, 1985; Wulf & Schmidt, 1997; see Van Rossum, 1990, for a review). However, some research suggests that the benefits of variable practice differ across populations and tasks, and may interact with other principles of motor learning (Lee et al., 1985; Shapiro & Schmidt, 1982). For example, the effects of variable practice may be more robust for children, who are less motorically experienced or skilled than adults (Chamberlin & Lee, 1993; Shapiro & Schmidt, 1982; but see Van Rossum, 1990).

Furthermore, constant and variable practice may affect relative timing (GMPs) and absolute timing (parameters) differently (e.g., Giuffrida et al., 2002; Lai & Shea, 1998; Lai, Shea, Wulf, & Wright, 2000; C. H. Shea, Lai, Wright, Immink, & Black, 2001). For example, Lai et al. (2000) found that constant practice improved relative timing, whereas variable practice improved absolute timing performance at transfer (consistent with the prediction that variable practice enhances the schema rule). Further, providing both constant and variable practice in two successive practice phases, with constant practice followed by variable practice (constant-variable), resulted in optimal learning of both relative and absolute timing, as compared to constant-constant, variable-variable, and variable-constant practice conditions (Lai et al., 2000). Lai et al. suggested that constant practice facilitates learning of the relative-timing pattern because the learner can focus on this aspect of the movement without having to extract the pattern from different parameterizations. Once the GMP is established, variable practice will enhance the schema rule (Lai et al., 2000).

Finally, there is evidence that practice variability interacts with other principles of motor learning such as practice amount (see above), feedback frequency, and practice schedule (e.g., Giuffrida et al., 2002; C. H. Shea & Kohl, 1991; Wulf & Shea, 2004). When using constant practice, too many trials may negatively affect long-term learning. In addition, variable practice appears to be more effective when task variants are practiced in random or serial order rather than in blocked order (e.g., Lee et al., 1985; Sekiya, Magill, Sidaway, & Anderson, 1994; C. H. Shea, Lai, et al., 2001; but see Pigott & Shapiro, 1984, for evidence that presenting small blocks in random order benefits learning in children).

Speech. While there has been some discussion of the benefits of variable practice over constant practice in textbooks on MSDs (e.g., Duffy, 2005), only one published study has addressed this principle in normal speech motor learning (Adams & Page, 2000). Adams and Page asked speakers to practice the utterance “Buy Bobby a poppy” with a specific overall movement time (utterance duration) under either constant or variable practice conditions. A constant practice group performed 50 practice trials of a single utterance duration (2,400 ms, approximately twice as slow as normal speech rate), whereas the variable practice group performed 25 practice trials with the 2,400-ms target duration and 25 trials with a target utterance duration of 3,600 ms (using a blocked practice schedule). Retention testing 2 days later involved only the 2,400-ms target. The variable-practice group had larger absolute error than the constant group during acquisition, but the groups did not differ at the end of the acquisition phase. Critically, the constant-practice group had larger absolute error than the variable group at retention testing, despite the fact that the constant group had received twice as many practice trials of the 2,400-ms target as the variable-practice group. These results suggest that variable practice benefits speech motor learning in unimpaired speakers, with respect to absolute time parameterization, consistent with evidence from nonspeech motor learning.

Rosenbek et al. (1973) speculated on the basis of three uncontrolled case studies that, for AOS, constant practice may be beneficial in the early stages of treatment or when the impairment is severe, while variable practice may be beneficial in later stages to facilitate the transfer of skills. This suggestion is consistent with the findings of Lai et al. (2000) that indicate a constant-variable practice order is optimal for learning all aspects of a movement. Although a handful of treatment studies for AOS using well-controlled single-subject experimental designs have demonstrated acquisition of targeted sounds and transfer to untrained sounds using variable practice (e.g., training of sounds in different phonetic contexts; Austermann Hula et al., in press; Ballard et al., 2007; Wambaugh et al., 1998, 1999), none of these studies compared variable- and constant-practice conditions. Thus, further studies are required to determine the relative benefits of variable and constant practice.

In sum, with respect to nonspeech motor learning, *variable practice appears to benefit the learning of absolute aspects of movements* (schema rules), whereas *constant practice early in practice benefits the learning of relative aspects of movements* (GMPs). Some evidence from unimpaired speakers suggests similar effects for speech motor learning, but more research is needed to determine how practice variability applies to impaired speakers.

Practice Schedule: Random Versus Blocked Practice

Random practice refers to a practice schedule in which different movements (i.e., GMPs) are produced on successive trials, and where the target for the upcoming trial is not predictable to the learner (e.g., for targets A, B, and C, a potential random trial sequence might be ACAB, BCAC, BCAB). Blocked practice refers to a practice schedule in which the learner practices a group of the same target movements before beginning practice on the next target (e.g., AAAA, BBBB, CCCC). Practice schedule differs from practice variability in two ways. First, practice variability refers to the number of different movements practiced (one for constant, multiple for variable), whereas practice schedule requires multiple movement targets that can be practiced in blocked or random order. Second, practice variability involves different parameterizations of one GMP, whereas practice schedule involves different GMPs (e.g., Sekiya et al., 1994; Wright, Black, Immink, Brueckner, & Magnuson, 2004). Also note that practice schedule is different from practice distribution (see above): both blocked and random practice may be spaced closer or further apart in time.

Nonspeech. Numerous studies have shown the benefits of random over blocked practice schedules (for retention) across a wide range of tasks (e.g., Lee & Magill, 1983; Lee et al., 1985; C. H. Shea, Kohl, & Indermill, 1990; J. B. Shea & Morgan, 1979; Wright et al., 2004; Wulf & Lee, 1993). J. B. Shea and Morgan (1979) were first to show that blocked practice schedules clearly enhanced performance during practice relative to random practice schedules, but that random practice had a clear advantage during retention testing (regardless of retention test schedule). Wright et al. (2004) showed that random practice, but not blocked practice, facilitates "chunking" (a relatively permanent integration of a sequence of movements into a single unit). Lee et al. (1985) demonstrated greater transfer following random than blocked practice schedules. In a prior study, Lee and Magill (1983) showed that both a random schedule and a serial schedule (e.g., ABC, ABC) resulted in greater retention than a blocked schedule, with no differences between the random and serial schedules. These findings suggest that it is the trial-to-trial change of target rather than the unpredictability of the upcoming trial that drives the benefit over blocked practice, although there is some recent evidence that random practice does provide learning benefits over serial practice in some cases (Osu, Hirai, Yoshioka, & Kawato, 2004). C. H. Shea et al. (1990) further observed that the benefits of random practice became stronger with more practice trials, suggesting an interaction with practice amount. Finally, random practice appears to facilitate learning of functional movement sequences in hemiparesis following unilateral stroke (Hanlon, 1996), as compared to blocked practice.

C. H. Shea and Wulf (2005) noted that practice schedule effects are not predicted by Schema Theory and discussed two alternative explanations: the reconstruction hypothesis and the elaboration hypothesis. According to the reconstruction hypothesis (Lee & Magill, 1983; Lee et al., 1985), the benefit of random over blocked practice arises from the repeated retrieval and construction of the response. The elaboration hypothesis (J. B. Shea & Morgan, 1979) claims that practicing several responses within a block (i.e., random practice) allows for a greater elaboration of the similarities and differences between the various responses, resulting in a more detailed and accurate representation of each response.

The benefits of random practice may be reduced by factors that increase task difficulty (e.g., inexperience of the learner, greater task complexity), perhaps due to a cognitive overload (Wulf & Shea, 2002). The picture is further complicated by findings indicating differential effects of practice schedule for GMPs and parameters (e.g., C. H. Shea, Lai, et al., 2001; Wright & Shea, 2001). Learning of absolute timing appears to be enhanced by random practice (C. H. Shea, Lai, et al., 2001; Wright & Shea, 2001), whereas the effects of practice schedule on relative timing depend on other factors such as the nature of error feedback, with greater retention for blocked practice in some cases (C. H. Shea, Lai, et al., 2001; but see Wright et al., 2004, for evidence that random practice facilitates GMP formation).

C. H. Shea, Lai, et al. (2001; see also Lai & Shea, 1998; Lai et al., 2000) proposed the *stability hypothesis* to account for the differential effects of random and blocked practice on relative- and absolute-timing learning. The stability hypothesis states that factors which promote trial-to-trial stability of performance during acquisition (e.g., blocked practice, reduced feedback, constant practice) promote the learning of relative-timing patterns, because the learner can focus on the invariant properties of the movement without having to take into account additional variation due to different parameterizations of the pattern. Once the GMP has been acquired, different parameterizations of the GMP can be practiced to improve the schemas. This view suggests that learning may be optimized by first practicing in blocked order and then in random order (similar to the Lai et al. study on constant vs. variable practice, discussed in the previous section).

Speech. Only two studies have directly compared blocked and random practice in speech (Adams & Page, 2000; Knock, Ballard, Robin, & Schmidt, 2000). Adams and Page examined random and blocked practice schedules in unimpaired speakers (using the same utterance-duration task). Although the random practice group showed greater absolute timing error during practice (except in the last acquisition block), the critical finding was that the random practice group was more accurate than the blocked practice group on retention tests.

Only one study to date has compared directly the effects of random and blocked presentation on speech motor learning in impaired speakers (Knock et al., 2000). Random versus blocked practice was studied in 2 individuals with severe AOS and aphasia, using an alternating treatments design where different targets were paired with random and blocked practice, and retention was examined 1 week and 4 weeks after treatment. They found no differences between conditions during acquisition, but at retention both individuals showed poorer maintenance of blocked practice targets than random practice targets, which in one case continued to improve. These differences were particularly evident at a 4-week retention probe.

While these findings are encouraging, they require replication across individuals, disorders, target behaviors, and contexts. Note that many recent treatment studies for AOS incorporate some form of random practice,[2] with some authors explicitly acknowledging the potential importance of random practice (Rose & Douglas, 2006; Strand & Debertine, 2000; Tjaden, 2000; Wambaugh et al., 1999; Wambaugh & Nessler, 2004). Wambaugh et al. (1999) and Wambaugh and Nessler (2004) suggested that random practice may reduce the occurrence of overgeneralization (substitution of practiced sounds for other sounds) and facilitate maintenance, perhaps by facilitating discriminatory abilities (cf. the elaboration hypothesis described earlier). Random practice resembles situations encountered in daily life (e.g., conversational discourse) more closely than blocked practice and thus may facilitate greater transfer to other contexts (Ballard, 2001; Wambaugh, Nessler, Bennett, & Mauszycki, 2004). Practice schedule has only been speculatively addressed in other MSDs (e.g., Schulz, Sulc, Leon, & Gilligan, 2000).

To summarize, there is substantial evidence that *random practice enhances motor learning* as indexed by retention and transfer tests in the nonspeech motor domain. This conclusion is complicated by the finding that random practice primarily benefits the learning of absolute aspects of movements (parameters) whereas blocked practice may benefit relative aspects of movements early in practice (GMPs; but see Wright et al., 2004), and by the finding that practice schedule may interact with other factors. In the speech domain, there is preliminary support for the use of random rather than blocked practice for both intact and impaired speech motor systems.

Attentional Focus: Internal Versus External Focus

Effects of focus of attention on motor learning have been considered for at least a century (Cattell, 1893/1947), but only recently have empirical studies been reported (e.g., Wulf, Höß, & Prinz, 1998; Wulf, McNevin, & Shea, 2001). An internal focus involves concentrating on aspects of movement such as kinetic, kinematic, and somatosensory information (e.g., arm movements in a golf swing). An external focus involves concentrating on external, but task-relevant, aspects of movement such as the effects of the movement (e.g., movement of the golf club) to achieve a goal (e.g., getting the ball in the hole). The movement *goal* is distinguished from the movement *effect*. The goal is the same in both internal and external focus conditions; the difference between the conditions lies in whether the learner concentrates on internal (e.g., kinetic, kinematic, somatosensory) aspects of the movement or on external, but task-relevant, aspects of the movement (e.g., golf club movement). The feedback in both conditions is also the same (e.g., both groups can see where the golf ball lands).

Nonspeech. An external focus of attention facilitates more accurate and less variable performance relative to an internal focus of attention, both during practice and on retention and transfer tests (e.g., Hodges & Franks, 2001; Vance, Wulf, McNevin, Töllner, & Mercer, 2004; Wulf, Lauterbach, & Toole, 1999; Wulf et al., 2001; see Wulf, 2007; Wulf & Prinz, 2001, for reviews). Using a golf-swing task, Wulf et al. (1999) found that an external-focus group scored better than an internal focus group during practice and retention testing (for which no focus instructions were provided). Wulf and McNevin (2003) further showed that merely distracting novice learners (by requiring them to shadow a narrative while performing the target task) did not improve learning relative to an internal focus (see also Beilock, Bertenthal, McCoy, & Carr, 2004). Thus, the external focus must be related to the task to be performed.

Wulf et al. (2001) proposed the *constrained-action hypothesis* to account for attentional focus effects. Under this view, individuals who adopt an internal focus of attention constrain or "freeze" their motor system in an attempt to control consciously otherwise automatic motor processes. A similar effect was observed when participants were not provided attentional focus instructions (e.g., Wulf et al., 1998), suggesting that learners may naturally adopt an internal focus of attention. An external focus of attention away from the motor system's targeted effector would allow for more automatically executed motor routines, thus enhancing both acquisition and learning. Wulf et al. (2001) provided evidence for more automatic processing with external than with internal focus by showing that participants' reaction times to a secondary task were faster when performing a primary (balance) task with an external focus than with an internal focus. Benefits of an external focus in a balance task have also been observed for individuals with Parkinson's disease (Landers et al., 2005). Finally, recent work indicates that an external attentional focus enhances performance of a nonspeech oral-motor task (Freedman, Maas, Caligiuri, Wulf, & Robin, 2007).

Speech. Although attentional focus effects extend to the oral-motor system (Freedman et al., 2007), no studies to date have examined the effects of attentional focus on speech motor learning. If such attentional focus effects apply to speech production, there would be important implications for treatment of MSDs. Speakers with MSDs may benefit from

[2] The qualification "some form of" relates to the fact that blocking can be applied at different levels, depending on how the targets are defined. For example, Wambaugh et al. (1998, 1999) entered different sounds into treatment sequentially (i.e., blocking by sound), but within each sound, 10 treatment words containing the sound were presented in random order.

adopting a strategy of external focus not only during practice but also in everyday communication situations. The optimal target for external focus in speech production remains to be determined. Most studies of attentional focus effects in nonspeech motor learning have employed tasks that involve an instrument (e.g., golf club), such that attention may be directed to the body movement or the instrument. While no such physically external objects are typically involved in speech production, a focus on acoustic output rather than speech articulators in therapy may parallel the nonspeech techniques. Given that speech appears to be planned in auditory space (Guenther et al., 1998), a focus on acoustics may be closer to the effect of the movement than a focus on the speech movements themselves.

In summary, an *external task-relevant focus has a strong demonstrated learning advantage over an internal focus* in the nonspeech motor domain, in that an external focus promotes movement automaticity and produces greater retention/transfer than an internal focus. Effects of attentional focus on speech motor control and learning have yet to be explored.

Movement Complexity: Simple (Part) Versus Complex (Whole)

Motor skills typically involve multiple components. It is intuitively appealing to split a complex movement into its component parts during practice so that the learner can concentrate on a single aspect of the skill. This approach is thought to minimize the cognitive load and avoid unnecessary practice on task aspects already mastered. This part-whole approach is common in many speech-remediation protocols and has been examined in the motor-learning literature.

Nonspeech. For tasks requiring rapid spatiotemporal coordination of different effectors, acquisition of the part may not transfer to the whole task, because performing the overall task may change the nature of the required motor control, especially if the whole movement is governed by a single GMP (Schmidt & Lee, 2005). For example, Lersten (1968) reported that practicing components of a rapid two-component movement did not transfer to performance of the whole movement. More recently, Hansen, Tremblay, and Elliott (2005) compared part practice and whole practice for relatively short movements. Although they did not find any differences between the conditions, the number of practice trials was small, and the movements consisted of relatively easily separated serial components, suggesting that the movement may not have been governed by a single GMP but rather by a sequence of GMPs.

There is some evidence that movements involving discrete, separable components might benefit from part practice (e.g., Mané, Adams, & Donchin, 1989; Newell, Carlton, Fisher, & Rutter, 1989; Park, Wilde, & Shea, 2004). Park et al. (2004) examined the effects of part practice versus whole practice using a serial-timing task involving 16 movement segments. A part-whole group practiced the first 8 elements on the first day of practice and all 16 elements on the second day, whereas a whole-whole group practiced the entire 16-element sequence on both days. Results revealed no group differences for retention of the entire sequence nor for transfer to the first 8 elements separately. However, the part-whole group outperformed the whole-whole practice group on a transfer test involving the last 8 elements of the sequence, indicating that the whole-whole group was less flexible than the part-whole group in breaking the movement sequence into subsequences.

However, a recent study examining the application of part versus whole practice to learning a complex surgical motor skill consisting of several relatively separable components showed that practice on the whole task resulted in greater learning than did part practice (Brydges, Carnahan, Backstein, & Dubrowski, 2007). This study thus suggests that even complex skills consisting of multiple components may benefit from whole practice.

Speech. Evidence has begun to emerge suggesting that targeting complex behaviors promotes learning relative to targeting simple behaviors (Ballard & Thompson, 1999; Gierut, 2001, 2007; Kiran, 2007; Kiran & Thompson, 2003; Maas, Barlow, Robin, & Shapiro, 2002; Schneider & Frens, 2005; Thompson, 2007; Thompson, Ballard, & Shapiro, 1998; Thompson & Shapiro, 2007). This evidence mostly relates to linguistic processing such as phonology (Gierut, 2001, 2007; Morrisette & Gierut, 2003; Rvachew & Nowak, 2001, 2003), syntax (Thompson et al., 1998; Thompson & Shapiro, 2007), and semantics (Kiran, 2007; Kiran & Thompson, 2003), rather than to speech motor control. These studies demonstrate that targeting complex behaviors (defined in terms of phonological, syntactic, or semantic structure) facilitates transfer to theoretically related simpler behaviors (e.g., Morrisette & Gierut, 2003; Thompson, Shapiro, Kiran, & Sobecks, 2003; but see Rvachew & Nowak, 2001, 2003), suggesting that the often-used treatment progression from simple to more complex behaviors may be less efficient than targeting more complex items early in treatment. This suggestion is consistent with the fundamental idea behind the challenge-point framework (Guadagnoli & Lee, 2004) that learners must be challenged in order for learning to occur.

The issue of complexity effects in speech motor learning has received little attention, yet it is especially relevant to the current debate about the use of nonspeech oral-motor exercises to improve speech production (Clark, 2003), and the common treatment approach of progressing from simple to complex tasks. Nonspeech oral-motor exercises may include repeated tongue elevations, lip-rounding, and tongue-strengthening exercises (Clark, 2003), the rationale being that these movements are shared with and therefore generalizable to speech production. However, such movements require much more extensive coordination across systems and effectors in speech production than in isolation. Thus, improvements in the control of such oral movements in isolation are unlikely to transfer to speech production (Clark, 2003). In the absence of evidence to the contrary, it seems that if the goal is to improve speech production, the behaviors selected for treatment should involve actual speech or speech-like productions. This approach can be expected to maximize both the learner's motivation and learning of the intricate and fine-tuned multisystem coordination necessary for speech.

Regarding treatment of MSDs, arguments have been made to begin with relatively easy sounds and progress to more difficult ones in the treatment of MSDs (e.g., Rosenbek et al., 1973). However, to date only two studies have directly examined the effects of speech movement complexity on speech motor learning in individuals with MSDs (Maas et al., 2002; Schneider & Frens, 2005). One difficult issue is how to define complexity of movements in general (Guadagnoli & Lee, 2004; Wulf & Shea, 2002) and speech movements in particular (Maas et al., 2002).

Maas et al. (2002) specifically addressed the effects of complexity in speech motor learning by providing treatment on complex or simple monosyllabic nonwords to 2 participants with moderate-severe AOS and aphasia. Complexity was defined in terms of the part-whole distinction (syllable structure), with three-element s-clusters composing the complex condition (e.g., *spleem*) and singletons making up the simple condition (e.g., *leem*). Each participant received treatment on both conditions, in different treatment phases. For one participant, practice on complex items generalized to singletons and two-element clusters, whereas singleton treatment only resulted in gains in singletons. The other participant demonstrated no difference between the two conditions in terms of generalization (generalization to singletons only in both conditions).

Schneider and Frens (2005) also compared the effects of treating complex and simple items for 3 individuals with moderate AOS and aphasia. These authors did not define complexity in terms of a part-whole distinction but in terms of the number of different gestures in four-syllable sequences (e.g., from simple to complex: /popopopo/, /popapipʌ/, /pomodoko/, /pomadikʌ/). The results indicated that training more complex sequences generalized to production of real words while training simple sequences did not.

The fact that complexity effects are not evident in all clients or in all contexts may reflect inadequate definitions of motor complexity and differences between individuals (e.g., age, severity, time after onset). Domains where complexity effects have been replicated, such as syntax (Thompson et al., 2003) and phonology (Morrisette & Gierut, 2003), have relatively clear, theoretically defined metrics of part-whole relationships, derived from linguistic theory. In the (speech) motor domain, such metrics must await further theoretical and empirical developments. Regarding individual differences, Guadagnoli and Lee's (2004) challenge-point framework suggests that task difficulty (nominal and functional) and the learner's skill level must be considered together to determine the optimal challenge point for each individual. One possibility is to define individual skill level using severity ratings. However, the challenge-point framework does not address impaired motor-control systems, and thus it remains to be seen whether severity level is related in a meaningful way to skill level.

In summary, the available evidence suggests that the *effects of part practice or whole practice depend on the nature of the task being learned,* with potential advantages of part practice for sequential movements with easily separable components, and potential advantages of whole practice for movements governed by a single GMP. While some preliminary evidence suggests benefits of using complex targets in treatment for AOS, further research is needed to determine whether and how complexity applies to speech treatments.

Structure of Augmented Feedback

Research aimed at the effects of augmented feedback (i.e., feedback that is given in addition to the individual's own intrinsic feedback) has a long history (for reviews, see Swinnen, 1996; Wulf & Shea, 2004). We focus on the effectiveness of different types of feedback (knowledge of results vs. knowledge of performance), the influence of feedback frequency, and the timing of feedback.

Feedback Type: Knowledge of Results Versus Knowledge of Performance

There are two types of augmented feedback: knowledge of results (KR) and knowledge of performance (KP; e.g., Schmidt & Lee, 2005). KR is information about the movement outcome, in relation to the goal, and is provided after the completion of a movement. It often refers to the deviation from a spatial or temporal goal, but it also includes more general information given, for example, by an instructor or therapist (e.g., "You missed the target"). In contrast, KP refers to the nature, or quality, of the movement pattern. This includes biofeedback, as well as qualitative information provided by an instructor (e.g., "Your lips were not closed enough for that sound"). Both KR and KP serve as a basis for error correction on subsequent trials and guide the performer to the correct movement.

Nonspeech. Studies of bimanual coordination indicate that KP is advantageous when the goal of the task is unknown (e.g., Newell, Carlton, & Antoniou, 1990). However, it does not appear to be more beneficial than simple outcome information (KR) when the task goal is clear (e.g., Swinnen, Walter, Lee, & Serrien, 1993), and may even be detrimental to learning when provided during task performance (Hodges & Franks, 2001), possibly due to the additional processing required to integrate this information into the ongoing movement.

Speech. Although often not reported, feedback type is an important component of every treatment protocol in MSDs. Treatment hierarchies typically combine these types of feedback; general KR of "correctness or incorrectness" is provided by verbal feedback or by the clinician's decision to either request another production attempt or move on to the next target elicitation. KP is inherently provided at levels of the hierarchy in which cuing and/or stimulation becomes more specific to the nature of the performance error observed, as in "You need to get your lips together to make that sound correctly."

While the effects of KR versus KP in speech treatment have not been investigated, the general principles regarding the utilization of KR versus KP in limb motor learning may apply to speech motor learning. Given that KP may be more beneficial when the learner does not possess a reliable internal representation of the movement goal (Newell et al., 1990), feedback type should be an important consideration in the treatment of MSDs. Emphasizing KP to maximize internalization of the movement goal may be more beneficial early in treatment, or for clients who cannot reliably distinguish correct from incorrect productions. KR feedback may be critical later in therapy and for clients who can better evaluate their own errors.

In sum, *KR and KP appear to be equally effective in most cases*; KP feedback appears useful when the task is novel or unclear, but may be detrimental when provided during performance. No studies have compared the effects of KR and KP on speech motor learning.

Feedback Frequency: High Versus Low Feedback Frequency

Feedback frequency refers to how often augmented feedback is provided during practice. Schemas are assumed to develop as a function of previous experience with a task and the corresponding outcome information (e.g., KR, an internally generated evaluation of the produced movement), and as such no learning should be possible in the absence of information about the outcome of the movement.

Nonspeech. Studies on feedback have shown an advantage for low-frequency feedback schedules (e.g., Winstein & Schmidt, 1990). Winstein and Schmidt, using a lever-positioning task, provided feedback after either 100% or 50% of the practice trials and found that, while performance of the two groups did not differ during practice, the 50% feedback group was more accurate at retention than the 100% group. This finding has been interpreted in terms of the *guidance hypothesis* (e.g., Salmoni, Schmidt, & Walter, 1984; Schmidt, 1991). According to this view, feedback guides the individual to the correct movement, but frequent feedback may have negative effects. Learners may become dependent on the feedback if they do not adequately process intrinsic feedback when augmented feedback is available. As a consequence, they may fail to develop adequate error detection and correction mechanisms (recognition schema) that would allow them to perform effectively when the augmented feedback is withdrawn.

Although these findings have been replicated in other studies (e.g., Nicholson & Schmidt, 1991), feedback frequency appears to interact with other factors such as practice variability, task complexity, and attentional focus (e.g., Dunham & Mueller, 1993; Lai & Shea, 1998; Wishart & Lee, 1997; Wulf, Lee, & Schmidt, 1994). The beneficial effects of reduced feedback frequency seem to be weaker during constant practice than during variable practice (see Wulf & Shea, 2004). The effects of feedback frequency also depend on skill complexity (Wulf & Shea, 2002). Learning of simple skills can benefit from reducing augmented feedback, but more frequent feedback might be required for the learning of complex skills (e.g., Swinnen, Lee, Verschueren, Serrien, & Bogaerds, 1997).

Interestingly, reduced frequency feedback appears to benefit GMP learning but not parameter learning (e.g., Wulf et al., 1994; Wulf & Schmidt, 1989; Wulf, Schmidt, & Deubel, 1993). Schema Theory (Schmidt, 1975) predicts the detrimental effects of reduced feedback on parameter learning because parameter learning only occurs when the movement outcome can be associated with the parameters selected for that movement. The benefits of reduced frequency feedback on GMP learning do not follow from Schema Theory but may be explained by the stability hypothesis (e.g., Lai & Shea, 1998; C. H. Shea, Lai, et al., 2001). Recall that the stability hypothesis claims that trial-to-trial stability enhances the learner's ability to extract invariant movement patterns. Frequent feedback induces more trial-to-trial corrections and thus less stability than does reduced frequency feedback (Lai & Shea, 1998).

Feedback frequency also appears to interact with error estimation. Using a force-production task, Guadagnoli and Kohl (2001) found that learning was enhanced for a low-frequency condition (feedback after 20% of practice trials), compared to a high-frequency condition (feedback after 100% of trials) when participants did not estimate their errors before they were provided feedback. However, when participants were required to estimate their errors, 100% feedback resulted in more effective learning than 20% feedback. According to Guadagnoli and Kohl, requiring participants to estimate their errors encourages them to engage in explicit hypothesis testing about the accuracy of their responses, and feedback allows for testing of such hypotheses. They argue that what the learner does before receiving KR influences how such KR will be used. Thus, this interaction suggests that the explicit tuning of internal error detection mechanisms in relation to an external reference of correctness is facilitated by frequent feedback. In contrast, when error estimations are not specifically required, learners might be more indirectly encouraged to engage in such processing under reduced feedback conditions.

Finally, attentional focus, which may be directed by augmented feedback, interacts with feedback frequency (Wulf, McConnel, Gärtner, & Schwarz, 2002). Feedback that directs the performer's attention to his or her body movements (internal focus feedback) is generally less effective than feedback that directs attention to the effects of the performer's movement on the environment (external focus feedback).[3] However, reducing the feedback frequency can diminish the detrimental effects of internal focus feedback. In contrast, external focus feedback, even if provided frequently, may benefit learning (Wulf et al., 2002).

Speech. Few studies have examined feedback frequency and speech motor learning. Guidelines for feedback delivery are often underspecified in treatment protocols for MSDs. Clinicians typically provide high-frequency, immediate feedback (Ballard et al., 2000). Recent work provides preliminary support for the benefits of reduced feedback frequency in intact speakers (Steinhauer & Grayhack, 2000) and speakers with AOS (Austermann Hula et al., in press). Austermann Hula et al. (Experiment 1) studied feedback frequency (100% vs. 60%) on the relearning of speech

[3]Note that this distinction between internal and external focus feedback does not correspond to the distinction between KP and KR. KP can induce both an internal focus and an external focus. For example, in relation to a golf swing, KP might be "your hip did not rotate enough" (internal) or "the club hit the ball too much on the left" (external). KR in either case would be whether the ball ended up in the hole, or how far from the hole it ended up (i.e., relating to the movement goal). Furthermore, attentional focus can be directed internally or externally even in the absence of feedback (through instructions), or with only KR in both focus conditions.

skills in AOS using an alternating-treatments design and found that reduced frequency feedback enhanced retention and transfer in 2 of the 4 participants. Issues related to stimulus complexity may have affected outcomes in the other 2 participants.

In sum, *reduced frequency feedback has benefits for motor learning*, especially for GMP learning, although frequent feedback appears to enhance parameter learning. Preliminary evidence suggests that reduced frequency feedback may also benefit speech motor learning.

Feedback Timing: Immediate Versus Delayed Feedback

Feedback timing refers to when feedback is provided relative to the performance of the task. Feedback is typically given after the completion of a movement (sometimes called "terminal" feedback) but can be provided simultaneously ("concurrent" feedback).

Nonspeech. Many professionals assume that concurrent feedback or immediate terminal feedback (as soon as possible after the movement) is most effective. In fact, concurrent feedback is detrimental to learning, compared with terminal feedback (e.g., Schmidt & Wulf, 1997; Vander Linden, Cauraugh, & Greene, 1993). Concurrent feedback greatly enhances performance during practice, but it results in clear performance decrements on retention and transfer tests (e.g., Park, Shea, & Wright, 2000; Schmidt & Wulf, 1997; Vander Linden et al., 1993). Similarly, giving feedback immediately is less effective for learning than delaying it for a few seconds (e.g., Swinnen, Schmidt, Nicholson, & Shapiro, 1990). The presumed reason is that concurrent and immediate feedback blocks the processing of intrinsic feedback during practice (e.g., guidance hypothesis; Salmoni et al., 1984).

However, there is an exception to this rule. If concurrently provided feedback induces an external focus of attention, it can facilitate learning (Hodges & Franks, 2001). C. H. Shea and Wulf (1999) had participants practice maintaining their balance on a moving platform and provided visual feedback about the position of the platform. Even though the concurrent feedback was redundant with participants' own visual and kinesthetic feedback, it facilitated learning, compared to no feedback. The concurrent feedback presumably benefited learning because it induced an external focus of attention and served as a constant reminder to maintain that focus.

Delaying the presentation of terminal feedback for a few seconds after the end of the movement can benefit learning (e.g., Swinnen et al., 1990). This effect has been attributed to learners spontaneously evaluating the movement, based on intrinsic feedback, in the interval before feedback is provided. In addition, specifically instructing participants to estimate their errors after the completion of a movement has been shown to enhance learning even further (e.g., Guadagnoli & Kohl, 2001; Swinnen et al., 1990).

Speech. Feedback timing has garnered little attention in our literature. Austermann Hula et al. (in press; Experiment 2) examined the effects of immediate versus delayed (5 s) feedback in 2 individuals with AOS. The results offered preliminary evidence that delayed feedback may enhance speech relearning for some individuals, as 1 of 2 participants showed enhanced retention in the delayed condition.

Summary feedback is another manipulation of interest. Summary feedback refers to provision of information about performance after several trials, and as such involves both delayed and reduced frequency feedback. Adams and colleagues (Adams & Page, 2000; Adams, Page, & Jog, 2002) compared the effects of different summary feedback schedules on the learning of a novel speech duration task. Participants were provided with a graphic display of each utterance's duration, either after every trial (Summary-1 group) or after every 5 trials (Summary-5 group). Typical speakers and those with hypokinetic dysarthria demonstrated the same pattern of results: The Summary-1 group had faster reduction in absolute error during the acquisition phase, but the Summary-5 group showed significantly better retention scores.

In short, *delayed feedback appears to enhance motor-skill learning* by facilitating internal movement evaluation. The limited available evidence from speech motor learning suggests that delayed feedback may also enhance speech motor learning.

Clinical Implications and Case Example

This tutorial reviewed evidence from the motor-learning literature as well as from the speech treatment literature regarding various conditions of practice. Perhaps the main conclusion that can be drawn is that at present, very little evidence exists regarding the effects of these conditions of practice on speech motor learning, in either neurologically intact or impaired speakers. As such, no firm recommendations can be made at this time, and further systematic research is needed to better understand principles of motor learning in speech motor learning in general and in treatment for MSDs in particular. Nonetheless, this review has several important clinical implications, which are highlighted in the following section. Finally, a fictional case example of an individual with AOS is used to illustrate how these principles of motor learning could be applied in the clinical setting.

Clinical Implications

A first important point emerging from this review is that the distinction between performance during practice versus retention and transfer is critical because performance during practice does not necessarily predict retention or transfer. Indeed, factors that promote performance during practice, such as constant practice or immediate feedback, may in fact be detrimental to learning. It is important that clinicians not be misled by changes observed during treatment. Incorporating daily or weekly retention and transfer tests into treatment programs for MSDs would help provide stronger evidence of the effects of treatment. Although obtaining long-term follow-up measures is often impossible or impractical in the clinical setting, one could use the first few minutes of a treatment session to assess shorter term retention (production of target responses without cues or feedback) and transfer (production of untrained items). Ultimately, long-term follow-up measures (e.g., 6 months, 1 year) are needed to assess the effectiveness of treatment, and future treatment studies should include such long-term follow-up tests whenever possible.

Second, one of the most consistent findings to emerge from the motor-learning literature is that relative (GMP) and absolute (parameter) aspects of movements often respond differently to practice and feedback variables. These findings pose serious clinical dilemmas in relation to speech motor control and the selection of treatment targets and variables, because in order to implement optimal conditions of practice and feedback, one must determine whether the selected treatment targets involve GMPs or parameters. However, determining GMPs and parameters in speech production is by no means a straightforward matter. As noted in the Background section above, the nature of speech motor programs remains a subject of debate, and it is likely that motor programs vary depending on the extent of practice (e.g., Levelt, Roelofs, & Meyer, 1999; Varley et al., 2006, relative to speech production; Klapp, 1995; Sakai et al., 2004; Wright et al., 2004, relative to nonspeech movements). One hypothesis is that aspects such as pitch level, speech rate, clarity, and loudness are controlled by parameter settings that scale the basic movement pattern captured in the speech motor programs (cf. Perkell et al., 2000). This view is consistent with the Nijmegen model of speech production (Levelt et al., 1999), according to which frequent syllables are associated with stored, precompiled motor programs that are parameterized for rate, pitch, loudness, and so on (Cholin, Levelt, & Schiller, 2006). Thus, despite ongoing debate about the nature of speech motor programs, a few tentative suggestions can be offered based on the distinction between absolute and relative aspects of movements.

Specifically, such treatment goals as modification of speech rate or loudness, if indeed controlled by a parameter, might benefit from variable and random practice (cf. Adams & Page, 2000). For example, if it is determined that slowing speech rate improves intelligibility for a given client, then one could select several target speech rates for a given utterance and elicit different target speech rates in random order. Limited available evidence from the speech motor-learning literature (Adams & Page, 2000; Adams et al., 2002) suggests that providing reduced frequency feedback would also enhance learning of absolute timing (i.e., speech rate).

In contrast, an example of GMPs in speech production might be lexical stress patterns. This hypothesis is reasonable given that stress patterns are defined in terms of the relative prominence (in terms of pitch, loudness, duration) of syllables in a word and are maintained despite variations in overall pitch level, loudness, or duration. Thus, according to this hypothesis, learning of stress patterns may benefit from reduced frequency, delayed feedback and blocked or constant practice schedules, at least early in practice. Once a given criterion of accurate performance or number of sessions has been reached, practice could shift to variable practice, to further enhance transfer. Variable practice can be blocked or random, though if a goal of therapy is to reduce the segmentation of speech that is caused by increased inter- and intrasegment durations, then random practice is necessary to facilitate concatenation into a larger unit (e.g., Wright et al., 2004).

Third, the nature of our measurements critically affects our conclusions, in particular with respect to the distinction between GMPs and parameters. Clinical measures of performance are often based on perceptual accuracy, with binary judgments (e.g., correct/incorrect) made on the basis of auditory perception. While perceptual judgments ultimately have important ecological validity, these measures may be fundamentally incapable of capturing fine-grained differences (Kent, 1996), including important gradual improvements that may occur, or distinctions between relative and absolute aspects of speech production. Use of finer measures may contribute to a better understanding of the underlying motor control and learning processes as well as their relation to the overall percept. Thus, clinicians may need to consider using instrumental measures of performance to supplement perceptual measures (e.g., Ballard et al., 2007; Schulz et al., 1999, 2000; Tjaden, 2000). Acoustic measures in particular can be useful, for example, to assess stress patterns (see Shriberg et al., 2003; Tjaden, 2000, for examples), absolute duration (cf. Adams & Page, 2000), and fundamental frequency. With respect to phonemic accuracy, potential acoustic measures include voice-onset time for plosives (cf. Ballard et al., 2007) and frequency of peak spectral energy (cf. Wambaugh, Doyle, West, & Kalinyak, 1995).

A final point to note is that, as clinicians, we must understand that conditions of practice and feedback interact with each other in complex ways. Thus, recommendations such as "random practice always enhances learning relative to blocked practice" or "reduced frequency feedback always enhances learning relative to high-frequency feedback" are misguided. Even an intuitive principle such as "a large number of practice trials enhances learning" is constrained by practice variability, in that intense constant practice decreases retention. Moreover, we must be aware that two principles may conflict with each other. For example, variable practice requires multiple target behaviors, which, given a fixed amount of practice time, necessarily limits the number of practice trials that can be performed for each of these behaviors (Wambaugh & Nessler, 2004). As yet, we simply do not know the optimal priorities, combinations, and orders of practice variables that would be most effective in the clinic. Certainly, clinicians may not want to include practice conditions that may reduce learning (as noted above; e.g., Strand & Debertine, 2000) until empirical data in speech motor (re)learning are obtained.

A Case Example

In this final section, we illustrate how the principles of motor learning discussed in this tutorial could be applied in a fictional case example of AOS, keeping in mind the caveat that most of these suggestions are based on evidence from nonspeech motor learning and thus require direct empirical testing in the context of treatment for MSDs. In addition, it should be noted that this example is not intended to be rigid or prescriptive. Rather, the intent is to stimulate further thinking about these conditions of practice and feedback by providing one of several possible ways to incorporate these principles into the treatment of MSDs. A brief case history and long-term goals for the case example are provided in Appendix A; a summary of the implementation of a motor-learning approach suggested for this case is presented in Appendix B. Examples of specific treatment goals are presented after the discussion of the motor-learning approach.

As can be seen in Appendix A, Jim's long-term goals include production of word-initial obstruents, clusters, and production of adequate stress patterns in disyllabic words. For each of these goals, acoustic measures can be used to supplement the perceptual measures, to track progress and/or to provide more reliable feedback during treatment (for examples of this latter approach, see Ballard et al., 2007, and Tjaden, 2000). For instance, voice-onset time and proportion of voicing can be used to assess the voicing distinction for plosives and fricatives, respectively (Ballard et al., 2007); the presence of intrusive schwa can be determined for clusters; measures of proportional syllable duration can be used to assess production of stress patterns (e.g., Tjaden, 2000).

A first step is to select a number of target items. Target selection involves a number of considerations, including functional relevance to facilitate motivation and potential for maximizing learning. For instance, there is evidence that targeting more complex items produces transfer to simpler items; in this case, targeting words with clusters (e.g., *Brad, truck, play*) might be more efficient than targeting singletons (e.g., *Jim, game, car*). Of course, functional relevance may dictate inclusion of simpler items as well (e.g., *game*). In the example, it is assumed that treatment targets include clusters and disyllabic words but not monosyllabic singleton words. Another consideration is that unwanted overgeneralization may occur if only items from one class are included as targets (cf. Ballard et al., 2007; Wambaugh & Nessler, 2004; see the discussion of practice schedule above). Thus, even though the client in the example primarily devoices voiced sounds, inclusion of voiceless sounds in treatment (e.g., *truck*) would be recommended to avoid substitution of voiced consonants for voiceless consonants (cf. Ballard et al., 2007).

In addition to selecting treatment targets, it is also important to select items that will not be treated directly but that can be used to assess transfer. Such a transfer set could include items with similar sounds or structures as those targeted in treatment (e.g., word-initial clusters such as *drive, bring, trip*), items relevant to the long-term goals but that were not practiced directly (e.g., CVC words such as *game, car, bet*), and items unrelated to the treatment targets (e.g., word-final clusters as in *hard, old, east*), so that treatment-specific effects can be determined. Treatment effects would be demonstrated by improvement on both targeted and related items but not on unrelated items. As noted in the previous section, a brief retention and transfer test can be administered at the beginning of each treatment session in order to track learning. These retention and transfer tests would ideally be administered without cuing or feedback, as the long-term goal would be for the client to be able to produce the targets independently.

Once treatment and transfer items have been selected, treatment can begin. Following the motor-learning literature, each session might begin with a prepractice component in which the target responses are explained, a reference of correctness is established, and several correct productions are elicited using modeling, cuing, and detailed KP feedback, to ensure that the client is able to produce the targets under optimal circumstances. In explaining the target responses, directing the client's attentional focus to the resulting sound rather than to the articulatory positions and movements involved might be more effective. KP feedback may be used to direct the client's attention to the sound (see footnote 3); such an "external" focus could be facilitated in some cases via the use of visual acoustic displays (e.g., Ballard et al., 2007). During prepractice, the client may also be informed about the conditions of practice and feedback during the actual practice or "drill" component of the session.

Actual practice can begin once each target type (e.g., a word-initial cluster, a disyllabic word) has been produced correctly in prepractice at least once. During the practice phase, maximizing the number of trials for each target is likely to enhance learning. As noted above, the number of target items is inversely proportional to the number of practice trials on each target. Given the importance of large amounts of practice, it may be better to select fewer targets and practice them numerous times than to select a large number of targets and practice them a few times. For this reason, only a small set of targets, three or four for each of two treatment goals, is proposed in the example; these seven items can then be practiced many times in each session. Production of other items can be assessed regularly to determine the degree of transfer. Of course, depending on the level of success and tedium experienced by the client, the set may be expanded during the course of treatment to ensure appropriate challenge and motivation.

During practice, target items should be elicited in random order rather than in blocked order, if possible, so that each trial requires full programming of the target. One way to implement a random schedule would be to create a number of stimulus cards for each item (e.g., five per item), shuffle the cards, and work through the stack as many times as possible during the session. This way, each target is unpredictable, and the total number of practice trials per item is controlled. If stress patterns are indeed governed by GMPs, then a practice schedule in which monosyllabic and bisyllabic (iambic and trochaic) stress patterns are presented in separate blocks may produce greater learning, at least early in practice. For instance, the first 10 min of practice could involve iambic disyllables only, and the next 10 min could involve monosyllabic targets, with the last 10 min devoted to trochaic disyllables; within each of these blocks, the specific target items would be randomized. Eventually, full randomization of all targets, which presumably approximates real-world communication, can be expected to promote transfer.

Similarly, variable practice is likely to enhance transfer. Variable practice can be achieved at different levels, such as by changing the elicitation cue (e.g., orthographic vs. picture stimuli), changing speech rate or loudness or pitch level of targets, changing carrier phrases, or changing the setting (e.g., clinic room vs. cafeteria). Such variations may also reduce tedium associated with drill practice and thus increase motivation.

With respect to feedback during practice, reducing the frequency of feedback can be expected to improve learning.

In order to reliably provide reduced frequency feedback (e.g., 60% of all trials), one could create a schedule with all trials and mark 60% of these trials for feedback, either randomly distributed or in a faded fashion (e.g., 100% for the first 10 items, 90% of the next 10 items, and so on; cf. Ballard et al., 2007). To avoid anticipation on the part of the client as to which trials will receive feedback, multiple feedback schedules can be created and used in different treatment sessions. Providing only KR feedback (correct/incorrect) in this phase would help maximize the number of drill trials. More detailed KP feedback can be provided during prepractice. Finally, providing feedback with a delay of a few seconds, rather than immediately following the response, presumably allows self-evaluation of the response by the client. Following clinician-feedback, the client can be given a few seconds to process this feedback and compare it with his or her own evaluation before presenting the next target.

To put the above suggestions together more concretely, sample treatment goals might be as follows: "In each session, Jim will produce the three target CCVC words correctly 80% of the time in the context of a picture naming task, with random presentation order, feedback on 60% of all productions, delayed feedback, and without modeling (done during prepractice)" and "In each session, Jim will produce the four target CVCVC words correctly 80% of the time in the context of a picture naming task, with blocked practice early in practice and moving to random practice once criterion is reached, using delayed feedback, reduced feedback frequency, and without modeling (done during prepractice)." One could add that "Early in practice, it may be advisable to present the monosyllabic words, iambic disyllabic words, and trochaic disyllabic words in separate blocks (within which targets are randomized); as improvement occurs, all targets may be randomized, and the responses may be elicited in different tasks and settings."

In sum, we have reviewed variables that affect nonspeech and speech motor learning, and suggested that while these variables have garnered little systematic testing in our field, they represent potentially critical variables with respect to speech motor (re)learning. Many of these variables are relatively easy to implement in treatment, regardless of the specific treatment program that is used, as illustrated in the case example. Clearly, much more research is needed to understand the application of principles of motor learning to MSDs, and hopefully this tutorial helps identify important clinical research questions, generate hypotheses, and design future treatment studies that will contribute to improving speech production in individuals with MSDs.

Acknowledgments

We thank Gayle DeDe for her helpful comments on an earlier version of this article.

References

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

Aichert, I., & Ziegler, W. (2004). Syllable frequency and syllable structure in apraxia of speech. *Brain and Language, 88,* 148–159.

American Speech-Language-Hearing Association. (2005). *Evidence-based practice in communication disorders* [Position statement]. Available from www.asha.org/policy.

Austermann Hula, S. N., Robin, D. A., Maas, E., Ballard, K. J., & Schmidt, R. A. (in press). *Effects of feedback frequency and timing on acquisition and retention of speech skills in acquired apraxia of speech. Journal of Speech, Language, and Hearing Research.*

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

Ballard, K. J. (2001). Response generalization in apraxia of speech treatments: Taking another look. *Journal of Communication Disorders, 34,* 3–20.

Ballard, K. J., Granier, J., & Robin, D. A. (2000). Understanding the nature of apraxia of speech: Theory, analysis, and treatment. *Aphasiology, 14,* 969–995.

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

Ballard, K. J., & Robin, D. A. (2007). Influence of continual biofeedback on jaw pursuit tracking in healthy adults and adults with apraxia plus aphasia. *Journal of Motor Behavior, 39,* 19–28.

Ballard, K. J., & Thompson, C. K. (1999). Treatment and generalization of complex sentence production in agrammatism. *Journal of Speech, Language, and Hearing Research, 42,* 690–707.

Basso, A. (2005). How intensive/prolonged should an intensive/prolonged treatment be? *Aphasiology, 19,* 975–984.

Beilock, S. L., Bertenthal, B. I., McCoy, A. M., & Carr, T. H. (2004). Haste does not always make waste: Expertise, direction of attention, and speed versus accuracy in performing sensorimotor skills. *Psychonomic Bulletin & Review, 11,* 373–379.

Brydges, R., Carnahan, H., Backstein, D., & Dubrowski, A. (2007). Application of motor learning principles to complex surgical tasks: Searching for the optimal practice schedule. *Journal of Motor Behavior, 39,* 40–48.

Cattell, J. M. (1947). Aufmerksamkeit und reaction [Attention and reaction]. In R. S. Woodworth (Ed. & Trans.), *Psychological research* (Vol. 1, pp. 252–255). Lancaster, PA: Science Press. (Original work published 1893).

Chamberlin, C. J., & Lee, T. D. (1993). Arranging practice conditions and designing instruction. In R. N. Singer, M. Murphey, & L. K. Tennant (Eds.), *Handbook on research in sport psychology* (pp. 213–241). New York: Macmillan.

Chiviacowsky, S., & Wulf, G. (2005). Self-controlled feedback is effective if it is based on the learner's performance. *Research Quarterly for Exercise and Sport, 76,* 42–48.

Cholin, J., Levelt, W. J. M., & Schiller, N. O. (2006). Effects of syllable frequency in speech production. *Cognition, 99,* 205–235.

Chumpelik, D. (1984). The PROMPT system of therapy: Theoretical framework and applications for developmental apraxia of speech. *Seminars in Speech and Language, 5,* 139–156.

Clark, H. M. (2003). Neuromuscular treatments for speech and swallowing: A tutorial. *American Journal of Speech-Language Pathology, 12,* 400–415.

Clark, H. M., & Robin, D. A. (1998). Generalised motor programme and parameterisation accuracy in apraxia of speech and conduction aphasia. *Aphasiology, 12,* 699–713.

Darley, F. L., Aronson, A. E., & Brown, J. R. (1975). *Motor speech disorders*. Philadelphia: W. B. Saunders.

Doyon, J., & Benali, H. (2005). Reorganization and plasticity in the adult brain during learning of motor skills. *Current Opinion in Neurobiology, 15,* 161–167.
Dromey, C., & Adams, S. (2000). Loudness perception and hypophonia in Parkinson disease. *Journal of Medical Speech-Language Pathology, 8,* 255–259.
Duffy, J. (2005). *Motor speech disorders: Substrates, differential diagnosis, and management* (2nd ed.). St. Louis, MO: Mosby-Yearbook.
Dunham, P., & Mueller, R. (1993). Effect of fading knowledge of results on acquisition, retention, and transfer of a simple motor task. *Perceptual and Motor Skills, 77*(3, Pt. 2), 1187–1192.
Fox, C. M., Morrison, C. E., Ramig, L. O., & Sapir, S. (2002). Current perspectives on the Lee Silverman Voice Treatment (LSVT) for individuals with idiopathic Parkinson disease. *American Journal of Speech-Language Pathology, 11,* 111–123.
Freedman, S. E., Maas, E., Caligiuri, M. P., Wulf, G., & Robin, D. A. (2007). Internal vs. external: Oral motor performance as a function of attentional focus. *Journal of Speech, Language, and Hearing Research, 50,* 131–136.
Gierut, J. A. (2001). Complexity in phonological treatment: Clinical factors. *Language, Speech, and Hearing Services in Schools, 32,* 229–241.
Gierut, J. A. (2007). Phonological complexity and language learnability. *American Journal of Speech-Language Pathology, 16,* 6–17.
Giuffrida, C. G., Shea, J. B., & Fairbrother, J. T. (2002). Differential transfer benefits of increased practice for constant, blocked, and serial practice schedules. *Journal of Motor Behavior, 34,* 353–365.
Guadagnoli, M. A., & Kohl, R. M. (2001). Knowledge of results for motor learning: Relationship between error estimation and knowledge of results frequency. *Journal of Motor Behavior, 33,* 217–224.
Guadagnoli, M. A., & Lee, T. D. (2004). Challenge point: A framework for conceptualizing the effects of various practice conditions in motor learning. *Journal of Motor Behavior, 36,* 212–224.
Guenther, F. H. (2006). Cortical interactions underlying the production of speech sounds. *Journal of Communication Disorders, 39,* 350–365.
Guenther, F. H., Ghosh, S. S., & Tourville, J. A. (2006). Neural modeling and imaging of the cortical interactions underlying syllable production. *Brain and Language, 96,* 280–301.
Guenther, F. H., Hampson, M., & Johnson, D. (1998). A theoretical investigation of reference frames for the planning of speech movements. *Psychological Review, 105,* 611–633.
Hanlon, R. E. (1996). Motor learning following unilateral stroke. *Archives of Physical Medicine and Rehabilitation, 77,* 811–815.
Hansen, S., Tremblay, L., & Elliott, D. (2005). Part and whole practice: Chunking and online control in the acquisition of a serial motor task. *Journal of Motor Behavior, 76,* 60–66.
Hodges, N. J., & Franks, I. M. (2001). Learning a coordination skill: Interactive effects of instruction and feedback. *Research Quarterly for Exercise and Sport, 72,* 132–142.
Janelle, C. M., Barba, D. A., Frehlich, S. G., Tennant, L. K., & Cauraugh, J. H. (1997). Maximizing performance effectiveness through videotape replay and a self-controlled learning environment. *Research Quarterly for Exercise and Sport, 68,* 269–279.
Johansen-Berg, H., Dawes, H., Guy, C., Smith, S. M., Wade, D. T., & Matthews, P. M. (2002). Correlation between motor improvements and altered fMRI activity after rehabilitative therapy. *Brain, 125,* 2731–2742.
Keele, S. W. (1968). Movement control in skilled motor performance. *Psychological Bulletin, 70,* 387–403.
Keetch, K. M., Schmidt, R. A., Lee, T. D., & Young, D. E. (2005). Especial skills: Their emergence with massive amounts of practice. *Journal of Experimental Psychology: Human Perception and Performance, 31,* 970–978.
Kelso, J. A. S. (1995). *Dynamic patterns: The self-organization of brain and behavior.* Cambridge, MA: MIT Press.
Kelso, J. A. S., Saltzman, E. L., & Tuller, B. (1986). The dynamical perspective on speech production: Data and theory. *Journal of Phonetics, 14,* 29–59.
Kent, R. D. (1996). Hearing and believing: Some limits to the auditory-perceptual assessment of speech and voice disorders. *American Journal of Speech-Language Pathology, 5,* 7–23.
Kent, R., & Rosenbek, J. (1983). Acoustic patterns of apraxia of speech. *Journal of Speech and Hearing Research, 26,* 231–249.
Kiran, S. (2007). Complexity in the treatment of naming deficits. *American Journal of Speech-Language Pathology, 16,* 18–29.
Kiran, S., & Thompson, C. K. (2003). The role of semantic complexity in treatment of naming deficits: Training semantic categories in fluent aphasia by controlling exemplar typicality. *Journal of Speech, Language, and Hearing Research, 46,* 773–787.
Klapp, S. T. (1995). Motor response programming during simple and choice reaction time: The role of practice. *Journal of Experimental Psychology: Human Perception and Performance, 21,* 1015–1027.
Knock, T., 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,* 653–668.
Krakauer, J. W. (2006). Motor learning: Its relevance to stroke recovery and neurorehabilitation. *Current Opinion in Neurology, 19,* 84–90.
Lai, Q., & Shea, C. H. (1998). Generalized motor program (GMP) learning: Effects of reduced frequency of knowledge of results and practice variability. *Journal of Motor Behavior, 30,* 51–59.
Lai, Q., Shea, C. H., Bruechert, L., & Little, M. (2002). Auditory model enhances relative-timing learning. *Journal of Motor Behavior, 34,* 299–307.
Lai, Q., Shea, C. H., Wulf, G., & Wright, D. L. (2000). Optimizing generalized motor program and parameter learning. *Research Quarterly for Exercise and Sport, 71,* 10–24.
Landers, M., Wulf, G., Wallmann, H., & Guadagnoli, M. (2005). An external focus of attention attenuates balance impairment in patients with Parkinson's disease who have a fall history. *Physiotherapy, 91,* 152–158.
Lee, T. D., & Genovese, E. D. (1989). Distribution of practice in motor skill acquisition: Different effects for discrete and continuous tasks. *Research Quarterly for Exercise and Sport, 60,* 59–65.
Lee, T. D., & Magill, R. A. (1983). The locus of contextual interference in motor-skill acquisition. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 9,* 730–746.
Lee, T. D., & Magill, R. A. (1985). Can forgetting facilitate skill acquisition? In D. Goodman, R. B. Wilberg, & I. M. Franks (Eds.), *Differing perspectives in motor learning, memory, and control* (pp. 3–22). Amsterdam: Elsevier.
Lee, T. D., Magill, R. A., & Weeks, D. J. (1985). Influence of practice schedule on testing schema theory predictions in adults. *Journal of Motor Behavior, 17,* 283–299.
Lersten, K. C. (1968). Transfer of movement components in a motor learning task. *Research Quarterly, 39,* 575–581.
Levelt, W. J. M., Roelofs, A., & Meyer, A. S. (1999). A theory of lexical access in speech production. *Behavioral and Brain Sciences, 22,* 1–38.
Liotti, M., Ramig, L. O., Vogel, D., New, P., Cook, C. I., Ingham, R. J., et al. (2003). Hypophonia in Parkinson's

disease: Neural correlates of voice treatment revealed by PET. *Neurology, 60,* 432–440.
Maas, E., Barlow, J., Robin, D., & Shapiro, L. (2002). Treatment of sound errors in aphasia and apraxia of speech: Effects of phonological complexity. *Aphasiology, 16,* 609–622.
Mané, A. M., Adams, J. A., & Donchin, E. (1989). Adaptive and part-whole training in the acquisition of a complex perceptual-motor skill. *Acta Psychologica, 71,* 179–196.
McNeil, M. R., Doyle, P. J., & Wambaugh, J. L. (2000). Apraxia of speech: A treatable disorder of motor planning and programming. In S. E. Nadeau, L. J. Gonzalez-Rothi, & B. Crosson (Eds.), *Aphasia and language: Theory to practice* (pp. 221–266). New York: Guilford Press.
McNeil, M. R., Robin, D. A., & Schmidt, R. A. (1997). Apraxia of speech: Definition, differentiation, and treatment. In M. R. McNeil (Ed.), *Clinical management of sensorimotor speech disorders* (pp. 311–344). New York: Thieme.
Morrisette, M. L., & Gierut, J. A. (2003). Unified treatment recommendations: A response to Rvachew and Nowak (2001). *Journal of Speech, Language, and Hearing Research, 46,* 382–385.
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., Fisher, A. T., & Rutter, B. G. (1989). Whole-part training strategies for learning the response dynamics of microprocessor driven simulators. *Acta Psychologica, 71,* 197–216.
Nicholson, D. E., & Schmidt, R. A. (1991). Scheduling information feedback to enhance training effectiveness. In *Proceedings of the Human Factors Society 35th Annual Meeting* (pp. 1400–1403). Santa Monica, CA: Human Factors Society.
Nudo, R. J., Wise, B. M., SiFuentes, F., & Milliken, G. W. (1996). Neural substrates for the effects of rehabilitative training on motor recovery after ischemic infarct. *Science, 272,* 1791–1794.
Osu, R., Hirai, S., Yoshioka, T., & Kawato, M. (2004). Random presentation enables subjects to adapt to two opposing forces on the hand. *Nature Neuroscience, 7,* 111–112.
Park, J. H., & Shea, C. H. (2003). Effect of practice on effector independence. *Journal of Motor Behavior, 35,* 33–40.
Park, J. H., & Shea, C. H. (2005). Sequence learning: Response structure and effector transfer. *Quarterly Journal of Experimental Psychology, 58A,* 387–419.
Park, J. H., Shea, C. H., & Wright, D. L. (2000). Reduced–frequency concurrent and terminal feedback: A test of the guidance hypothesis. *Journal of Motor Behavior, 32,* 287–296.
Park, J. H., Wilde, H., & Shea, C. H. (2004). Part-whole practice of movement sequences. *Journal of Motor Behavior, 36,* 51–61.
Perkell, J. S., Guenther, F. H., Lane, H., Matthies, M. L., Perrier, P., Vick, J., et al. (2000). A theory of speech motor control and supporting data from speakers with normal hearing and with profound hearing loss. *Journal of Phonetics, 28,* 233–372.
Pigott, R. E., & Shapiro, D. C. (1984). Motor schema: The structure of the variability session. *Research Quarterly for Exercise and Sport, 55,* 41–45.
Ramig, L. O., Countryman, S., Thompson, L. L., & Horii, Y. (1995). Comparison of two intensive speech treatments for Parkinson disease. *Journal of Speech and Hearing Research, 38,* 1232–1251.
Ramig, L. O., Sapir, S., Countryman, S., Pawlas, A. A., O'Brien, C., Hoehn, M., & Thompson, L. L. (2001). Intensive voice treatment (LSVT®) for patients with Parkinson's disease: A 2 year follow-up. *Journal of Neurology, Neurosurgery, and Psychiatry, 71,* 493–498.
Ramig, L. O., Sapir, S., Fox, C., & Countryman, S. (2001). Changes in vocal loudness following intensive voice treatment (LSVT®) in individuals with Parkinson's disease: A comparison with untreated patients and normal age-matched controls. *Movement Disorders, 16,* 79–83.
Rhodes, B. J., Bullock, D., Verwey, W. B., Averbeck, B. B., & Page, M. P. A. (2004). Learning and production of movement sequences: Behavioral, neurophysiological, and modeling perspectives. *Human Movement Science, 23,* 699–746.
Rijntjes, M., & Weiller, C. (2002). Recovery of motor and language abilities after stroke: The contribution of functional imaging. *Progress in Neurobiology, 66,* 109–122.
Robertson, E. M., Pascual-Leone, A., & Miall, R. C. (2004). Current concepts in procedural consolidation. *Nature Neuroscience Reviews, 5,* 1–7.
Robey, R. R. (1998). A meta-analysis of clinical outcomes in the treatment of aphasia. *Journal of Speech, Language, and Hearing Research, 41,* 172–187.
Robin, D. A., Maas, E., Sandberg, Y., & Schmidt, R. A. (2007). Motor control and learning and childhood apraxia of speech. In P. K. Hall, L. S. Jordan, & D. A. Robin (Eds.), *Developmental apraxia of speech: Theory and clinical practice* (2nd ed.). Austin, TX: Pro-Ed.
Rose, M., & Douglas, J. (2006). A comparison of verbal and gesture treatments for a word production deficit resulting from acquired apraxia of speech. *Aphasiology, 20,* 1186–1209.
Rosenbek, J. C., Lemme, M. L., Ahern, M. B., Harris, E. H., & Wertz, R. T. (1973). A treatment for apraxia of speech in adults. *Journal of Speech and Hearing Disorders, 38,* 462–472.
Rvachew, S., & Nowak, M. (2001). The effect of target-selection strategy on phonological learning. *Journal of Speech, Language, and Hearing Research, 44,* 610–623.
Rvachew, S., & Nowak, M. (2003). Clinical outcomes as a function of target selection strategy: A response to Morrisette and Gierut. *Journal of Speech, Language, and Hearing Research, 46,* 386–389.
Sakai, K., Hikosaka, O., & Nakamura, K. (2004). Emergence of rhythm during motor learning. *Trends in Cognitive Sciences, 18,* 547–553.
Salmoni, A. W., Schmidt, R. A., & Walter, C. B. (1984). Knowledge of results and motor learning: A review and critical reappraisal. *Psychological Bulletin, 95,* 355–386.
Schmidt, R. A. (1972). The case against learning and forgetting scores. *Journal of Motor Behavior, 4,* 79–88.
Schmidt, R. A. (1975). A schema theory of discrete motor skill learning. *Psychological Review, 82,* 225–260.
Schmidt, R. A. (1991). Frequent augmented feedback can degrade learning: Evidence and interpretations. In J. Requin & G. E. Stelmach (Eds.), *Tutorials in motor neuroscience* (pp. 59–75). Dordrecht, The Netherlands: Kluwer Academic Publishers.
Schmidt, R. A. (2003). Motor schema theory after 27 years: Reflections and implications for a new theory. *Research Quarterly for Exercise and Sport, 74,* 366–375.
Schmidt, R. A., & Bjork, R. A. (1992). New conceptualizations of practice: Common principles in three paradigms suggest new concepts for training. *Psychological Science, 3,* 207–217.
Schmidt, R. A., & Lee, T. D. (2005). *Motor control and learning: A behavioral emphasis* (4th ed.). Champaign, IL: Human Kinetics.
Schmidt, R. A., & Wulf, G. (1997). Continuous concurrent feedback degrades skill learning: Implications for training and simulation. *Human Factors, 39,* 509–525.
Schneider, S. L., & Frens, R. A. (2005). Training four-syllable CV patterns in individuals with acquired apraxia of speech: Theoretical implications. *Aphasiology, 19,* 451–471.

Schulz, G. M., Dingwall, W. O., & Ludlow, C. L. (1999). Speech and oral motor learning in individuals with cerebellar atrophy. *Journal of Speech, Language, and Hearing Research, 42,* 1157–1175.

Schulz, G. M., Sulc, S., Leon, S., & Gilligan, G. (2000). Speech motor learning in Parkinson disease. *Journal of Medical Speech-Language Pathology, 8,* 243–247.

Sekiya, H., Magill, R. A., Sidaway, B., & Anderson, D. I. (1994). The contextual interference effect for skill variations from the same and different generalized motor programs. *Research Quarterly for Exercise and Sport, 65,* 330–338.

Shapiro, D. C., & Schmidt, R. A. (1982). The schema theory: Recent evidence and developmental implications. In J. A. S. Kelso & J. E. Clark (Eds.), *The development of movement control and co-ordination* (pp. 113–150). New York: Wiley.

Shea, C. H., & Kohl, R. M. (1991). Composition of practice: Influence on the retention of motor skills. *Research Quarterly for Exercise and Sport, 62,* 187–195.

Shea, C. H., Kohl, R. M., & Indermill, C. (1990). Contextual interference: Contributions of practice. *Acta Psychologica, 73,* 145–157.

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,* 737–760.

Shea, C. H., Lai, Q., Wright, D. L., Immink, M., & Black, C. (2001). Consistent and variable practice conditions: Effects on relative and absolute timing. *Journal of Motor Behavior, 33,* 139–152.

Shea, C. H., & Wulf, G. (1999). Enhancing motor learning through external-focus instructions and feedback. *Human Movement Science, 18,* 553–571.

Shea, C. H., & Wulf, G. (2005). Schema theory: A critical appraisal and reevaluation. *Journal of Motor Behavior, 37,* 85–101.

Shea, C. H., Wulf, G., Park, J. H., & Gaunt, B. (2001). Effects of an auditory model on the learning of relative and absolute timing. *Journal of Motor Behavior, 33,* 127–138.

Shea, J. B., & Morgan, R. L. (1979). Contextual interference effects on the acquisition, retention, and transfer of a motor skill. *Journal of Experimental Psychology: Human Learning & Memory, 5,* 179–187.

Shriberg, L. D., Campbell, T. F., Karlsson, H. B., Brown, R. L., McSweeney, J. L., & Nadler, C. J. (2003). A diagnostic marker for childhood apraxia of speech: The lexical stress ratio. *Clinical Linguistics & Phonetics, 17,* 549–574.

Spencer, K. A., & Rogers, M. A. (2005). Speech motor programming in hypokinetic and ataxic dysarthria. *Brain and Language, 94,* 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,* 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,* 137–145.

Strand, E. A., & Debertine, P. (2000). The efficacy of integral stimulation intervention with developmental apraxia of speech. *Journal of Medical Speech-Language Pathology, 8,* 295–300.

Swinnen, S. P. (1996). Information feedback for motor skill learning: A review. In H. N. Zelaznik (Ed.), *Advances in motor learning and control* (pp. 37–66). Champaign, IL: Human Kinetics.

Swinnen, S. P., Lee, T. D., Verschueren, S., Serrien, D. J., & Bogaerds, H. (1997). Interlimb coordination: Learning and transfer under different feedback conditions. *Human Movement Science, 16,* 749–785.

Swinnen, S., Schmidt, R. A., Nicholson, D. E., & Shapiro, D. C. (1990). Information feedback for skill acquisition: Instantaneous knowledge of results degrades learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 16,* 706–716.

Swinnen, S., Walter, C. B., Lee, T. D., & Serrien, D. J. (1993). Acquiring bimanual skills: Contrasting forms of information feedback for interlimb decoupling. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 19,* 1328–1344.

Thompson, C. K. (2007). Complexity in language learning and treatment. *American Journal of Speech-Language Pathology, 16,* 3–5.

Thompson, C. K., Ballard, K. J., & Shapiro, L. P. (1998). The role of syntactic complexity in training *wh*-movement structures in agrammatic aphasia: Optimal order for promoting generalization. *Journal of the International Neuropsychological Society, 4,* 661–674.

Thompson, C. K., & Shapiro, L. P. (2007). Complexity in treatment of syntactic deficits. *American Journal of Speech-Language Pathology, 16,* 30–42.

Thompson, C. K., Shapiro, L. P., Kiran, S., & Sobecks, J. (2003). The role of syntactic complexity in treatment of sentence deficits in agrammatic aphasia: The complexity account of treatment efficacy (CATE). *Journal of Speech, Language, and Hearing Research, 46,* 591–607.

Tjaden, K. (2000). Exploration of a treatment technique for prosodic disturbance following stroke. *Clinical Linguistics & Phonetics, 14,* 619–641.

Vance, J., Wulf, G., McNevin, N., Töllner, T., & Mercer, J. (2004). EMG activity as a function of the performer's focus of attention. *Journal of Motor Behavior, 36,* 450–459.

Vander Linden, D. W., Cauraugh, J. H., & Greene, T. A. (1993). The effect of frequency of kinetic feedback on learning an isometric force production task in nondisabled subjects. *Physical Therapy, 73,* 79–87.

Van Riper, C., & Irwin, J. (1958). *Voice and articulation*. Englewood Cliffs, NJ: Prentice Hall.

Van Rossum, J. H. A. (1990). Schmidt's schema theory: The empirical base of the variability of practice hypothesis. A critical analysis. *Human Movement Science, 9,* 387–435.

Van Vliet, P., & Wulf, G. (2006). Extrinsic feedback for motor learning after stroke: What is the evidence? *Disability and Rehabilitation, 28,* 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., Doyle, P. J., West, J. E., & Kalinyak, M. M. (1995). Spectral analysis of sound errors in persons with apraxia of speech and aphasia. *American Journal of Speech-Language Pathology, 4,* 186–192.

Wambaugh, J. L., Duffy, J. R., McNeil, M. R., Robin, D. A., & Rogers, M. A. (2006). Treatment guidelines for acquired apraxia of speech: A synthesis and evaluation of the evidence. *Journal of Medical Speech-Language Pathology, 14*(2), xv–xxxiii.

Wambaugh, J. L., Kalinyak-Fliszar, M. M., West, J. E., & Doyle, P. J. (1998). Effects of treatment for sound errors in apraxia of speech and aphasia. *Journal of Speech, Language, and Hearing Research, 41,* 725–743.

Wambaugh, J. L., Martinez, A. L., McNeil, M. R., & Rogers, M. A. (1999). Sound production treatment for apraxia of speech: Overgeneralization and maintenance effects. *Aphasiology, 13,* 821–837.

Wambaugh, J. L., & Nessler, C. (2004). Modification of sound production treatment for apraxia of speech: Acquisition and generalization effects. *Aphasiology, 18,* 407–427.

Wambaugh, J. L., Nessler, C., Bennett, J., & Mauszycki, S. C. (2004). Variability in apraxia of speech: A perceptual and VOT analysis of stop consonants. *Journal of Medical Speech-Language Pathology, 12,* 221–227.

Winstein, C. J., & Schmidt, R. A. (1990). Reduced frequency of knowledge of results enhances motor skill learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 16,* 677–691.

Wishart, L. R., & Lee, T. D. (1997). Effects of aging and reduced relative frequency of knowledge of results on learning a motor skill. *Perceptual and Motor Skills, 84*(3, Pt. 1), 1107–1122.

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

Wright, D. L., & Shea, C. H. (2001). Manipulating generalized motor program difficulty during blocked and random practice does not affect parameter learning. *Research Quarterly for Exercise and Sport, 72,* 32–38.

Wulf, G. (2007). *Attention and motor skill learning*. Champaign, IL: Human Kinetics.

Wulf, G., Hõβ, M., & Prinz, W. (1998). Instructions for motor learning: Differential effects of internal versus external focus of attention. *Journal of Motor Behavior, 30,* 169–179.

Wulf, G., Lauterbach, B., & Toole, T. (1999). Learning advantages of an external focus of attention in golf. *Research Quarterly for Exercise and Sport, 70,* 120–126.

Wulf, G., & Lee, T. D. (1993). Contextual interference in movements of the same class: Differential effects on program and parameter learning. *Journal of Motor Behavior, 25,* 254–263.

Wulf, G., Lee, T. D., & Schmidt, R. A. (1994). Reducing knowledge of results about relative versus absolute timing: Differential effects on learning. *Journal of Motor Behavior, 26,* 362–369.

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

Wulf, G., & McNevin, N. (2003). Simply distracting learners is not enough: More evidence for the learning benefits of an external focus of attention. *European Journal of Sport Science, 3*(5), 1–13.

Wulf, G., McNevin, N., & Shea, C. H. (2001). The automacity of complex motor skill learning as a function of attentional focus. *The Quarterly Journal of Experimental Psychology, 54A,* 1143–1154.

Wulf, G., & Prinz, W. (2001). Directing attention to movement effects enhances learning: A review. *Psychonomic Bulletin & Review, 8,* 648–660.

Wulf, G., & Schmidt, R. A. (1989). The learning of generalized motor programs: Reducing the relative frequency of knowledge of results enhances memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15,* 748–757.

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

Wulf, G., Schmidt, R. A., & Deubel, H. (1993). Reduced frequency feedback enhances generalized motor program learning but not parameterization learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 19,* 1134–1150.

Wulf, G., & Shea, C. H. (2002). Principles derived from the study of simple motor skills do not generalize to complex skill learning. *Psychonomic Bulletin and Review, 9,* 185–211.

Wulf, G., & Shea, C. H. (2004). Understanding the role of augmented feedback: The good, the bad, and the ugly. In A. M. Williams & N. J. Hodges (Eds.), *Skill acquisition in sport: Research, theory and practice* (pp. 121–144). London: Routledge.

Yorkston, K. M., Beukelman, D. R., Strand, E., & Bell, K. R. (1999). *Clinical management of motor speech disorders in children and adults*. Boston: Little Brown.

Received August 31, 2006
Revision received April 9, 2007
Accepted October 15, 2007
DOI: 10.1044/1058-0360(2008/025)

Contact author: Edwin Maas, Department of Speech, Language, and Hearing Sciences, University of Arizona, P.O. Box 210071, Tucson, AZ 85721-0071. E-mail: emaas@email.arizona.edu.

Appendix A

Case History and Treatment Goals for the (Fictional) Case Example

Case history

Jim is a 55-year-old man who suffered a stroke 6 months ago. As a result, he has a mild nonfluent aphasia and a moderate-severe apraxia of speech, according to the consensus criteria for AOS (Wambaugh, Duffy, McNeil, Robin, & Rogers, 2006). Jim's speech errors are most prominent on pressure consonants (plosives, fricatives, affricates) and in clusters, especially in word-initial position. Jim frequently devoices voiced consonants. Jim lives at home with his partner, Shirley, and together they have two children, Brad and Violet. Jim completed community college and has been manager of a small auto body shop for 20 years. He would like to go back to work. In his spare time, he enjoys playing poker with his friends, going to football games, and camping.

Long-term goals (see text for sample treatment goals)

1. Increase correct production of word-initial pressure consonants. By the end of treatment, Jim will produce each affricate, fricative, and plosive correct in word-initial position at least 80% of the time, as determined via perceptual judgments in the context of reading a list of 15 CVC words in random order without cuing or feedback.
2. Increase correct production of stress patterns in disyllabic words. By the end of treatment, Jim will produce at least 80% of disyllabic (iambic and trochaic) CV(C)CVC words with perceptually appropriate stress, in the context of reading a list of 10 disyllabic words in random order without cuing or feedback.
3. Increase correct production of word-initial clusters. By the end of treatment, Jim will produce word-initial clusters correctly (determined perceptually) at least 80% of the time in monosyllabic CCV(C) words, in the context of reading a list of 15 CCV(C) words in random order without cuing or feedback.

Appendix B

Summary of Implementation of a Motor-Learning Approach for the Case Example

Prepractice

Begin each session with prepractice, in which to address and review the following:

—*Motivation*: To facilitate motivation, select a number of potential functional targets together with the client, for example, those relating to his family's names, his interests, and his work. Potential examples might include *Jim, Shirley, Violet, Brad, game, play, card, chip, football, camping, car, sedan, truck, hotel*. From this set, select the more complex targets for treatment, for instance, those with clusters (e.g., *Brad, truck, play*) and two syllables (e.g., *Shirley, Violet, sedan, hotel*). More complex items may be expected to produce transfer to simpler words.
—*Explaining the target responses*: Any explanations about how sounds are made should be provided in prepractice and not during practice where feedback should only relate to the correctness of a response. Too much detail during practice may be distracting.
—*Focus of attention*: Instead of directing attention to the articulatory movements involved in producing a speech sound, direct the focus to how the target should sound.
—*Establish a reference of correctness*: Explain the criteria for a correct response, for example, that all sounds must be produced, the response should be fluent, and so on.
—*Ensure stimulability*: Elicit at least one acceptable response for each target before moving to the practice phase, to ensure that the target is within the range of capability.

Practice

—*Large amounts of practice*: In order to (re)establish motor patterns, it is necessary to produce a large number of repetitions per target. It may be better to select fewer targets and practice them numerous times than to select a large number of targets and practice them a few times. For example, from the potential targets above, it was suggested to select three targets for the second goal and four targets for the third goal, and practice those seven items many times each session. Transfer to other words of functional relevance can be assessed intermittently over the course of treatment (using the end-of-treatment reading lists noted in the long-term goals; Appendix A).
—*Practice distribution*: Evidence from nonspeech motor learning suggests that spacing a given number of trials and sessions farther apart enhances learning. However, the only study to date in the speech domain suggests that there is no difference between four sessions per week versus two sessions per week. At present, it is unknown what the optimal practice distribution is for speech motor learning.
—*Random practice*: During practice sessions, the practice stimuli should be presented in random order rather than in blocked order. For example, instead of eliciting 10 trials of *Brad,* then 10 trials on *truck,* etc., present the items randomly.
—*Variability of practice*: Varying the targets and therapy environment may facilitate transfer. For example, targets can be varied by changing loudness, or pitch. The therapy environment can be varied by moving to a different location in the clinic.
—*Low-frequency feedback*: Feedback on whether the targets were correctly produced should only be on approximately 60% of the practice trials, to avoid disruption of the learning process and overreliance on the clinician's judgments instead of learning to self-monitor.
—*Delayed feedback*: Feedback should not be given immediately after an attempt; the client should be given time to self-evaluate the movement. In addition, a time delay should also be given (once feedback is provided) before moving on to the next production, to allow time for comparing self-evaluation of the production with the judgment of the clinician.