Relevant to this special series on movement science, a brief overview of research in the field of motor learning is provided. A distinction between learning and performance is emphasized with respect to experimental design and the evaluation of laboratory and clinical intervention techniques. Intrinsic and extrinsic feedback are defined. Basic principles of motor learning pertaining to the use of augmented feedback or knowledge of results (KR) are reviewed. Particular emphasis is placed on recent research regarding the effects of selected KR variations (KR relative frequency, bandwidth KR, and KR delay) on motor performance and learning in healthy young adults. Results are discussed in terms of short-lasting temporary performance effects and relatively long-lasting learning effects. Theoretical and practical implications from this research are discussed. It is suggested that it is appropriate to use the principles obtained through laboratory experimentation as guidelines rather than as exact recommendations when applying basic research findings to clinical practice. [Winstein CJ. Knowledge of results and motor learning—implications for physical therapy. Phys Ther. 1991;71:140-149.]

Key Words: Feedback, Learning, Motor skills, Movement, Rehabilitation.

Introduction

The acquisition of motor skills is fundamental to human life. The ability of a person to acquire with practice or experience the proficiency to execute coordinated motor actions enables that person to have a wide range of human experiences. These experiences may range from grasping a cup after the disabling consequences of a cerebrovascular accident to flying an airplane through turbulence. The search to understand the processes underlying the control of motor behavior has motivated considerable research in various fields including psychology, kinesiology, neurophysiology, and engineering. Part of this research has been directed toward understanding the principles governing the acquisition of motor skills. Numerous variables considered important determinants of motor learning have been studied. Among the research areas related to skill acquisition are the use of feedback, modeling and demonstration, transfer of training, mental practice, prepractice instructions, part to whole task practice, variability in practice, and contextual variety. Some of these research topics, such as mental practice and modeling and demonstration, overlap with, and are often presented as topics within, the domain of sport psychology. Certainly, one of the most critical of these learning variables, aside from practice itself, is feedback to the performer. One form of such feedback, termed "knowledge of results" (KR), is the augmented extrinsic information about task success provided to the performer. This information serves as a basis for error correction on the next trial and thus can be used to achieve more effective performance as practice continues. Because of the importance of feedback, the effects of a number of KR variations, such as the frequency, delay, and precision with which error information is delivered, have been studied.

This selected review is concerned with laboratory research pertaining to the effects on motor learning of three KR variations. Specifically, data will be summarized from experiments examining the effects on motor skill learn-
Before reviewing the KR research, it is necessary to first make a distinction between motor learning and motor control. Second, to better familiarize the reader with the field of motor learning, a brief overview is provided of recent and future directions of research within this domain. Finally, consideration is given to the potential relevance of motor learning research to physical therapy.

**Research In Motor Learning**

Schmidt defines motor control as "an area of study dealing with the understanding of the neural, physical, and behavioral aspects of movement" and motor learning as "an area of study focusing on the acquisition of skilled movements as a result of practice." Space does not permit a detailed discussion of the history of motor learning research, nor would such an excursion be particularly germane to the main focus of this article. The interested reader should refer to the work of Schmidt and Christina for more detailed discussions. To more fully appreciate the research paradigms and theoretical perspectives underlying research in motor learning, in general, and in KR, in particular, one must consider the important influence of the parent discipline of psychology.

During what has been referred to as the "task-approach" period, from about 1940 through the late 1950s, research in motor learning was motivated primarily by the dominant stimulus-response (S-R) formulation prevalent in behavioral psychology at that time. Research during that period used real-world motor tasks, and the emphasis was on performance outcomes. Since the late 1960s, motor learning research has been dominated by the information-processing approach prevalent in cognitive psychology (see article by Light in this special series on movement science for further discussion of the information-processing view). The focus of this approach was more on the cognitive processes underlying skill acquisition than on outcomes. To better focus on the information-processing operations during motor skill acquisition, simple motor tasks, such as those involving the linear slide or positioning apparatus, were generally used. This "process approach," in contrast to the task approach, was strongly advocated by psychologists such as Pew and Adams as a necessary step toward the development of a general theory of motor learning.

In 1971, prompted by the growing body of research in motor learning and the availability of a relatively large empirical database from linear positioning tasks, Adams introduced the first theory of motor learning. Invoking a cybernetics model, Adams proposed the closed-loop theory of motor learning in which the motor response is seen primarily as driven by feedback from the moving limb. Later, allowing for the principles of open-loop control in which the response is controlled primarily by a motor program, Schmidt proposed the schema theory of discrete motor learning. Both Adams's and Schmidt's theoretical contributions stimulated substantial basic and applied research activity.

With regard to future directions for motor learning research, Schmidt has advocated a return to the task approach and has emphasized both the theoretical and practical (eg, applied) contributions of such an approach. Christina similarly advocates independent, but cooperative, endeavors at the basic and applied research levels. He suggests the need to extend research into the applied areas of health with an emphasis on gerontology and physical rehabilitation.

**Motor Learning and Physical Therapy**

The shift away from applied motor learning research during the "process-approach" period has recently been a source of debate in the physical education community. Some argue that motor learning research is meaningful for physical education practitioners, whereas others argue that motor learning research is not relevant to the needs and interests of motor skill teachers. A similar argument could be raised with respect to the relevance of motor learning research to physical therapy.

Motor learning research has focused primarily on healthy individuals learning novel motor skills (see Mulder for an exception). Although direct application of the principles of motor learning obtained through laboratory research may not be immediately possible; a considerable foundation has been established that may be useful to physical therapy once the proper boundary conditions are established. For example, research from the motor skills literature pertaining to the use of augmented feedback could be used to provide guidelines for physical therapy rehabilitation protocols. How often should the therapist provide feedback during a treatment session? What kind of feedback is best for motor learning? The knowledge base in motor learning can be used to provide at least partial answers to these and numerous other clinically relevant questions.

Certainly, when viewed within the broader context of movement science, many—if not most—of the practices of physical therapy involve some form of movement training or reeducation (eg, back education programs, post-stroke gait training). Likewise, patients participating in these various physical therapy programs are involved in some form of movement learning or relearning. If we assume that the principles of motor learning gleaned through research with healthy subjects may be similar to those of motor learning for our patients with orthopedic and neurologic disorders, it could be argued that knowledge of these principles becomes highly relevant to the science and practice of physical therapy.

Several individuals recognized the relevance of motor learning research...
to physical therapy over 20 years ago. One might ask why this valuable integration was never more fully developed. One explanation may be that in an attempt to more clearly define its own domain, the physical therapy profession turned inward and, in so doing, disassociated itself from related, but nonclinical, fields. Now, there is increasing evidence that the pendulum has begun its backswing.

**Feedback and Knowledge of Results**

In general, sensory information associated with motor behavior can be divided into two major categories distinguished by their temporal relationship with the action. Sensory information available prior to the action may be considered as **feedforward** and includes information related to the environment and the performer with respect to the upcoming action. In contrast to feedforward, **feedback** is sensory information that is available during or after the action. Feedback includes information related to the sensations associated with the movement itself (eg, feel, sound) as well as information related to the result of the action with respect to the environmental goal. These two sources of feedback have been referred to as intrinsic and extrinsic, respectively.

Intrinsic feedback is inherent to the action and includes kinesthetic, visual, cutaneous, vestibular, and auditory signals collectively termed “response-produced feedback.” These normal sources of intrinsic feedback may be absent or damaged in the patient with certain peripheral or central lesions. In contrast to intrinsic feedback, extrinsic feedback is information provided from an external source and is supplemental to the intrinsic sources mentioned above. Extrinsic, or augmented, feedback can be provided to the performer in various ways. It can be verbal or nonverbal, and it can be provided concurrently, immediately following, or delayed in time with respect to the relevant action.

Extrinsic feedback relating to the **outcome** of an action with respect to the environmental goal is referred to as **KR**. Consider the following clinical example. The goal is to rise from a sitting position to a standing position in a given amount of time. At the termination of the trial, KR might be given in terms of the amount of time it took to complete the task (eg, 1.25 seconds). In comparison, extrinsic feedback, which provides information about the nature of the movement **pattern** underlying the goal outcome, is called “knowledge of performance” (KP) (see article by Gentile for further discussion). Using the same clinical example, KP might be given by indicating the degree to which the patient leaned his or her trunk and head forward prior to rising from the chair. In contrast to KR, which in many everyday behaviors tends to be redundant with intrinsic feedback, KP represents the kind of extrinsic feedback most often given to performers (and our patients) in natural (or clinical) settings. Knowledge of results, however, has been the focus of a majority of the experimental and theoretical research on information feedback and learning. This preference for KR in empirical work has primarily been due to the ease with which it can be obtained, manipulated, and quantified in the experimental laboratory. Although more research using KP variables is needed, the existing studies indicate that KP variables behave similarly to KR variables with regard to motor learning.

**The Knowledge-of-Results Research Paradigm**

Researchers examining the relationship of feedback to motor skill learning must control the multiple sources of feedback that are available in natural settings. Frequently, an experimental environment is created in which the usefulness of intrinsic feedback pertaining to the movement outcome is minimized. Feedback is then systematically reintroduced (usually in the form of KR), and its effects on the learning process are examined. Such an experimental design may closely mimic the conditions of a patient with sensory deficits who is unable to effectively use intrinsic feedback for motor control and thus must rely on the extrinsic feedback provided by the therapist.

This research paradigm is based on the premise that KR functions with respect to these artificial laboratory tasks in the same way that intrinsic feedback functions in real-life movement situations. Processes facilitated by the use of extrinsic feedback in the laboratory, such as error correction or the development of an internal reference of correctness, therefore, are thought to be similar to those processes facilitated by the use of intrinsic feedback sources in natural settings in which KR is unavailable or redundant.

The KR research paradigm has not escaped criticism by those who question the generalizability of research findings, from the usually one-dimensional motor tasks used in the paradigm to the multidimensional, coordinated actions found outside the laboratory. Currently, little is known about the complex interactions of the multiple sources of feedback available through more natural actions. The principles gleaned from the KR research paradigm may offer at best only minimal insight into the functioning of intrinsic feedback in multidimensional movements. These principles may be quite different in real-life situations. The evidence is quite extensive, however, that KR is an important determinant of behavioral change in these laboratory settings. Thus, an understanding of the principles governing how information feedback affects motor behavior has practical implications or at least could provide guidelines for teachers, therapists, and performers. It has provided a critical cornerstone for theory pertaining to the learning process itself.

**Learning Versus Performance**

Research in motor learning requires an operational definition of "learning." Scientists have typically found it useful to define learning as a set of internal processes associated with practice or experience leading to a
Although some researchers, using classical conditioning paradigms, have begun to isolate the neural substrates associated with learned behaviors in animals, behavioral researchers investigating humans must usually infer from a change in behavior that learning has occurred. Not all behavioral changes, however, reflect learning. This caveat becomes an important consideration for designing experiments in the laboratory as well as assessing the effects of a treatment intervention in the clinic. Of the numerous variables that influence behavioral change, some (eg, fatigue, drugs) are thought to effect only temporary changes, others (eg, practice) are considered to change behavior in more permanent ways, and still others (eg, KR) are thought to effect both temporary and relatively permanent changes. The motor learning researcher, as well as the clinician, is usually interested in those variables thought to effect relatively permanent changes in behavior. How are changes in behavior attributable to temporary factors distinguished from changes attributable to more permanent effects?

One way motor learning researchers experimentally distinguish the relatively permanent effects of various practice variables from the temporary effects is by using a transfer design. This design typically involves two distinct phases: (1) an acquisition, or practice, phase in which different groups receive treatments representing various levels of the independent variable (eg, different schedules of extrinsic feedback) and (2) a transfer phase in which all groups are transferred to a common level of the independent variable (eg, no feedback). The transfer phase is sufficiently separate in time from the acquisition phase such that the temporary effects from the independent variable have had adequate time to dissipate. Thus, performance in the transfer phase can be said to reflect the learning produced by the independent variable during the acquisition phase.

Knowledge of Results and Motor Learning

In general, KR is considered a practice variable that is capable of effecting both temporary and relatively permanent (ie, learning) changes in performance. Given this potentially ambiguous state, proper experimental techniques such as transfer designs must be used to determine which KR variations are important for learning (see article by Salmoni et al1 for further discussion).

The motor learning literature and clinical practice protocols are surprisingly consistent in showing that, during the practice phase in most tasks, nearly any variation that increases the availability (eg, immediacy, precision, frequency, number of channels) of information feedback benefits performance and increases the rate of improvement over trials.43 Because performance benefits from such conditions, it is easy to assume that these conditions also benefit learning and retention. Recent research, however, has revealed that certain variations of KR that provide information feedback less often during practice prove to be more beneficial for long-term learning and retention than practice conditions with feedback provided more often. These feedback variations that appear to enhance learning pertain to the scheduling of KR during practice and include (1) KR relative frequency, which is the proportion of trials receiving KR; (2) bandwidth KR, which provides KR after trials for which performance is outside a given error tolerance range; and (3) KR delay, which provides KR following some temporal delay after completion of a response.46 These potentially important KR variations have been examined exclusively with healthy subjects learning novel laboratory tasks. Results from each KR variation will be reviewed first, followed by a general discussion with comments regarding clinical implications for physical therapy.

Relative frequency of knowledge of results. Operationally, the relative frequency of KR is the proportion of practice trials for which KR is provided, whereas absolute frequency refers to the total number of trials for which KR is provided in a practice session. These KR frequency variables are relevant to structuring the learning environment and thus have received considerable attention. One of the earliest and most influential studies of KR relative frequency, conducted over 30 years ago by Bilodeau and Bilodeau, involved a simple lever-pulling task. Four different relative-frequency practice conditions were produced by holding the number of KR trials constant (ie, absolute frequency was 10) and varying the number of interspersed no-KR practice trials. In their experiment, the KR relative frequencies were 10%, 25%, 33%, and 100%. Because the number of practice trials was allowed to vary with relative frequency, the 100% group practiced the task for 10 trials and received KR after each trial. The 33% group practiced the task for 30 trials and received KR after every third trial. The 25% group practiced the task for 40 trials and received KR after every fourth trial. Finally, the 10% group practiced the task for 100 trials and received KR after every 10th trial. Blindfolded subjects pulled a vertically extended hand lever to a goal position. Knowledge of results about the direction and amount of position error was presented in accord with the particular relative-frequency schedule.

Comparison of the four groups on each of the trials immediately following each KR trial (ie, KR + one trial) revealed no differences attributable to relative frequency. This finding supported an assumption that the no-KR trials interspersed among the KR presentations were not particularly useful. This assumption was later shown to be invalid. For the 10% group, as expected, performance deteriorated on the sets of nine intervening no-KR trials. Bilodeau and Bilodeau con-
cluded that "learning is related to the absolute frequency, and not the relative frequency of KR."47(p382) Because a transfer or retention test was not conducted, the learning-performance distinction, long known to learning psychologists,48 could not be evaluated. Bilodeau and Bilodeau's experiment, therefore, provides evidence with regard to motor performance, but not with regard to motor learning.

Later experiments by Ho and Shea69 and Johnson and colleagues (RW Johnson, G. W. Wicks, D. Ben-Sira; unpublished data; 1981) extended the work of Bilodeau and Bilodeau47 by using no-KR retention tests and similarly simple motor tasks. Results from these studies suggested that KR relative frequency was an important variable for learning. Apparently, conditions with less frequent KR, though detrimental to immediate performance during practice, were beneficial to learning as measured on a no-KR retention test. These experiments, and Bilodeau and Bilodeau's study, confounded the total number of trials and KR relative frequency, making the results difficult to interpret. The apparent beneficial effects from practice in low relative-frequency conditions could have arisen simply from the amount of practice and not the relative KR frequency.

Recently, an attempt was made to optimize the beneficial learning effects attributed to practice in reduced KR relative-frequency conditions by manipulating the schedule of KR and no-KR trials within the practice session.37 Two groups of subjects practiced a complex spatial-temporal movement pattern over a 2-day period under either high (100%) or moderate (50%) relative-frequency KR conditions. In this experiment, the number of trials (196 per day) was held constant across groups, thus allowing relative and absolute frequency to covary. A "faded" KR schedule was used in the 50% condition, such that on each day the proportion of KR trials was relatively high early in practice (100%) but was gradually reduced toward the end of practice (25%). Following 2 days of practice, a 5-minute (immediate) and a 1-day (delayed) no-KR retention test was administered to each group.

Figure 1 shows the average error scores for the two relative-frequency groups across trial blocks during the 2-day acquisition phase and the immediate and delayed retention phases. There were no overall group differences during the acquisition phase. On the immediate no-KR retention test, the 50%-KR group performed with a slightly lower error score (8.5 versus 9.2) than the 100% group, and, on the delayed no-KR retention test, the 50%-KR group performed 35% better (10.0 versus 12.1) than the 100%-KR group. As illustrated in Figure 1, performance for both groups deteriorated (ie, error scores increased) between the end of acquisition and retention, but the 100%-KR group showed greater deterioration than did the 50%-KR group.

These findings run counter to the conventional viewpoint that less frequent KR should degrade learning.87, 90 Instead, a condition with less frequent KR was shown to enhance learning, at least as measured on a no-KR retention test. From a practical standpoint, conditions that provide KR more frequently may be appealing because of the temporary effects on performance. These effects, however, may not be beneficial to learning in the form of retention performance when compared with conditions with less frequent KR. Not surprisingly, when performance was examined on trials for which KR was not provided, the subjects in the 50%-KR condition demonstrated larger error scores than did subjects in the 100%-KR condition on corresponding acquisition trials.91 This relationship, however, was reversed when performance scores for the groups were examined in the delayed no-KR retention test.

These results were replicated in a second experiment87 in which a delayed KR retention test was used. In this experiment, the same KR schedule was used as in the previous experiment during a 2-day practice period. Instead of a no-KR retention test, however, a 12-trial, 1-day delay retention test was administered in which KR was provided after each trial. Surprisingly, the 50%-KR group performed significantly better than the 100%-KR group even on this 100% KR retention test. The faded 50% relative-frequency KR schedule seemed to facilitate the development of a capa-
bility for responding that appeared immune to the particular superficial characteristics of the practice and retention conditions. Although a superficial similarity between low relative-frequency KR practice and retention test conditions cannot account for these findings, it may be that a similarity in processing operations, as suggested by Lee’s concept of transfer appropriateness, could account for these results.

Bandwidth knowledge of results. In bandwidth KR, feedback is provided only if the performance response is outside a given range (ie, window of acceptable performance). This procedure is quite different from the KR relative-frequency variation thus far considered, in that the absence of KR actually informs the subject that the previous response was acceptable. Bandwidth KR, therefore, provides two kinds of feedback: 

(1) feedback that is motivating for trials that fall inside the bandwidth (eg, “Good, do that again.”) and 

(2) feedback that is informative with respect to errors for trials that fall outside the bandwidth.

Sherwood’s study investigated the effects of bandwidth KR with a ballistic timing task in which a lever was to be moved through a target amplitude in exactly 200 milliseconds. He used 5% and 10% bandwidth KR conditions and one control condition for which KR was provided on every trial, termed the 0% bandwidth. In the 5% bandwidth KR condition, subjects received movement-time KR if their absolute error was greater than 10 milliseconds. Similarly, the 10% group received KR if movement time error was greater than 20 milliseconds. Sherwood’s results showed no differences between groups during acquisition and no differences in retention in terms of performance accuracy. The 10% bandwidth KR group, however, performed more consistently from trial to trial and with higher overall accuracy on the retention test than either the 5% bandwidth KR or control groups.

These retention-test results with bandwidth KR are consistent with those for KR relative frequency. Overall accuracy was highest for those subjects who practiced in conditions with less frequent KR trials. On the average, in Sherwood’s study, the 5% bandwidth KR group received KR at an average frequency of 54% of the trials, whereas the 10% bandwidth KR group received KR at an average frequency of 31%. Because larger bandwidth KR conditions result in reduced KR relative frequencies compared with smaller bandwidth conditions, it was unclear how much of the beneficial effects from larger bandwidths were due simply to the reduced relative frequency.

Lee and Carnahan attempted to unravel the contribution of KR relative frequency from the bandwidth KR variation by using an experimental procedure known as “yoking.” They compared the performance of subjects in four KR conditions using a timing task with a 500-millisecond goal. Two of the groups had similar conditions to those used in Sherwood’s study, namely 5% and 10% bandwidth KR groups that received verbal KR about their timing errors according to the prescribed bandwidths. The other two groups had conditions designated the yoked-5% and yoked-10% conditions, that were created by pairing each of the bandwidth subjects with a yoked counterpart who received the same KR schedule. Hence, subjects in the yoked conditions received KR about their own performance on precisely the same trials as the bandwidth KR subjects. Because the paired subject’s KR schedule was being used, however, the KR was not customized to the yoked subject’s performance, nor was the absence of KR indicative of “good” performance as it was in the bandwidth KR conditions.

The results of Lee and Carnahan’s experiment indicated that the beneficial effects of a bandwidth KR condition on learning were not simply due to a relative-frequency KR effect. During acquisition, the bandwidth KR condition seemed to enhance accuracy and stability over that achieved in the yoked relative-frequency KR conditions. During retention, although there were no significant differences between groups with respect to accuracy, the subjects in the bandwidth KR conditions were less variable (within-subject variable error) in their performance than those in the yoked relative-frequency KR conditions. The beneficial learning effects of the bandwidth KR variation over a pure relative-frequency KR condition thus appear to be most pronounced with respect to movement consistency. Because skilled performances are characterized as being both accurate and stable, feedback variations that enhance performance consistency are equally as important as those that promote accuracy.

Knowledge of results delay. Another KR variation known as KR delay refers to the timing of KR. The KR delay interval is the amount of time between the completion of the action and the presentation of the KR. Theoretically, this interval has been thought to contribute to forgetting of the movement memory by allowing decay of the memory trace. Thus, lengthening the interval between movement response and KR was thought to be detrimental to learning. According to this view, shortening the KR delay interval as much as possible should benefit learning. It is interesting that high-technology, computer-assisted feedback devices recently available for various kinds of movement retraining are designed to provide instantaneous feedback to the performer (ie, the KR delay has been essentially eliminated). The KR delay review by Salmoni et al. however, indicated that, in general, increasing the KR delay interval does not appear to degrade learning and, in some cases, might even enhance learning. Conversely, in this same review, the authors suggested that there were some hints from the literature that shortened KR delays might degrade learning.

Swinnen and colleagues recently compared skill acquisition for a group of subjects receiving 100% KR after a
short delay with another group receiving 100% KR instantaneously. In the first experiment, a timing task with two movement reversals was used. Three KR conditions were used: (1) an instantaneous KR condition in which the subject was presented with KR immediately after completion of the movement, (2) a delayed KR condition in which the subject had an 8-second unfilled interval between the completion of the movement and the presentation of KR, and (3) an estimation condition in which the subject had an 8-second interval between the completion of the movement and the presentation of the KR during which he or she was required to orally estimate his or her movement time.

The results of this first experiment, illustrated in Figure 2, showed no pronounced differences in performance between the three groups during the acquisition phase. On the 10-minute and 2-day retention tests, however, the instantaneous KR group showed marked deterioration in performance relative to the other two groups. On the delayed (2-day) retention test, the estimation group performed significantly better than the instantaneous KR group, whereas the delayed KR group performed at a level between the other two groups. These results suggested that instantaneous KR may have degraded learning by blocking or interfering with important information-processing operations associated with the development of error-detection capabilities.46 The estimation group had significantly less error than the instantaneous KR group on the delayed retention test, suggesting that evaluation of response errors during the KR interval was beneficial for learning.

In a second experiment, a complex coincident-timing task and two KR delay conditions were used. The instantaneous KR group received 100% KR 210 milliseconds after response completion, and the delayed KR group received 100% KR 3.2 seconds after response completion. By the end of the second day of practice, the instantaneous KR group demonstrated a significantly worse performance than the delayed KR group. This same relationship persisted through several retention tests (immediate and delayed), demonstrating the detrimental effects of instantaneous KR on learning.

Swinnen and associates suggest that the use of frequent or instantaneous feedback can discourage the processing of other kinds of information, such as intrinsic response-produced feedback that would lead to the learning of the capability to detect errors in future performances.86

From a practical standpoint, this research suggests that an adequate KR delay interval be provided to allow for the processing of relevant response and task information. This method of providing KR is in direct contrast to that of some practitioners, who advocate the provision of feedback immediately or continuously.53,54 It may be that early in the reacquisition phase, the patient needs more immediate KR to "get the idea of the task," but care should be taken to prevent overreliance on the extrinsic feedback at the expense of the development of an internal reference of correctness necessary for long-term retention and learning. Persons with neurological deficits may require longer, or perhaps even shorter, KR intervals than healthy age-matched controls. In addition, relevant to designing computer-assisted feedback devices, it is apparent from this work that, although the provision of instantaneous feedback may be beneficial for performance during practice, it can be detrimental for learning and retention.

**Theoretical and Practical Implications**

In the relative-frequency, bandwidth, and KR delay variations previously discussed and in the summary KR variation not addressed in this article (see articles by Schmidt and colleagues55,56), those conditions in which KR was provided less frequently or less immediately were more beneficial for motor learning than conditions in which KR was provided more frequently or without delay. Some researchers56,57,46,51 have suggested that these beneficial KR practice conditions invoke certain information-processing operations.
that are beneficial for learning. The following discussion briefly highlights some of the current hypotheses regarding what these beneficial processes might be. For a more detailed discussion with associated arguments, the original sources should be consulted.

One view, termed the "guidance hypothesis," holds that when KR is provided frequently, the subject begins to rely on its guiding properties. The KR is said to act like a crutch that is not needed to the degree to which it is used. This overdependence on KR may actually prevent the processing of important task-related information (eg, response-produced feedback) and thus block the development of error-detection capabilities needed at the time of retention and transfer.

Another view, termed the "consistency hypothesis," is supported by a number of studies. This notion suggests that frequent KR induces frequent response modifications called "maladaptive short-term corrections." These frequent response modifications make performance inconsistent from trial to trial. This induced response variability interferes with the establishment of a stable action plan necessary for later response production.

Finally, it has been suggested that a schedule with intermittent KR allows for a more obvious contrast between performance driven by KR and performance that is independent of KR (ie, during no-KR trials). It is evident that performance errors are greater during no-KR trials than during KR trials. The nature and awareness of errors may only become apparent to the subject following the next KR trial. In contrast to a schedule with frequent KR, an intermittent KR schedule provides an opportunity for the subject to obtain information about performance errors (eg, drift from the target pattern) that occur when KR is not directly influencing the response. This process of comparison may be beneficial for learning in that it gives the subject information about errors during performance that is not influenced by any extrinsic feedback. Although performance for trials not preceded by KR appears by immediate standards to be relatively poor (ie, less accurate, although it may be more consistent, especially with bandwidth KR), the information-processing operations suggested to occur during this period seem to be beneficial for learning.

The KR research presented suggests a need to reexamine treatment approaches that advocate performance accuracy, strong guidance (either manual, tactual, or verbal), frequent and continuous feedback, and avoidance of errors or "abnormal" movements. Considering the learning-performance distinction with regard to these treatment practices may well account for the often-cited minimal "carry-over" and limited retention of newly acquired motor skills. Perhaps a new set of treatment guidelines based on the KR literature would prove useful.

Highly skilled and experienced therapists appear to intuitively use techniques analogous to the faded, intermittent, bandwidth, and delayed KR conditions, although their rationale may not be well developed or understood from the perspective of motor learning principles. In any attempt to bridge the gap between basic research and practice, it is important to understand that the principles gleaned through laboratory experimentation are best used as guidelines for practice, as opposed to specific do's and don'ts. Direct application of the KR laboratory research to clinical intervention should be cautiously used until the proper clinical studies have been conducted. Applied research from which more specific recommendations can be made in the practical domain is needed.

In terms of clinical procedures, these findings imply that the once-advocated use of feedback in a manner consistent with the adage "more is better" no longer seems appropriate. The view advocated by motor-learning researchers and clinicians regarding the beneficial learning effects of feedback variations that tend to increase the amount or frequency of KR should be challenged.

It seems clear from these initial findings with healthy subjects that certain information-processing operations facilitated by conditions with less information feedback are better for learning than those with more frequent or more immediate feedback. Although this finding might seem counterintuitive, it appears that forcing the learner to actively develop problem-solving strategies independently of the guidance provided by feedback (and the therapist) is actually beneficial for motor learning.

An understanding of the processes underlying these beneficial effects will be important for new developments in theory, practice, and the training of physical therapists (as learners of new motor skills). For the growing knowledge base of physical therapy, an understanding of the principles underlying the use and misuse of augmented information feedback could foster new insights, challenge present practices, lead to hypothesis testing, and provide for the development of theory as a basis for new or revised therapeutic and educational practices.

**Motor Learning, Physical Therapy, and Future Directions**

Although it can be argued that the knowledge base of motor learning—particularly as related to the use of feedback (KR and KP)—is highly relevant to physical therapy, few entry-level education programs have incorporated this knowledge base in their curricula (although there is evidence that this situation is changing). Educational curricula have developed, in concert with the needs generated by professional practices rather than discipline-based knowledge. Early in our professional growth, we drew heavily from the medical model, and the foundations for our practices generally were based on what we thought to be fundamental clinical sciences. As we develop a broader
perspective for both entry-level and postgraduate education, our knowledge base must reflect that development. As programs in movement science begin to represent the norm in physical therapy, our entry-level curricula will also evolve in a similar manner.

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References


50. Thorndike EL. The law of effect. Psychol Rev. 1932:7:122–222.


52 Lee TD, Carnahan H. Bandwidth knowledge of results and motor learning: more than just a relative frequency effect. *Q J Exp Psychol* [A]. In press.


60 Lee TD, Carnahan H. When to provide knowledge of results during motor learning: scheduling effects. *Human Performance*. In press.


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