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Principles derived from the study of simple skills do not generalize to complex skill learning

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We review research related to the learning of complex motor skills with respect to principles developed on the basis of simple skill learning. Although some factors seem to have opposite effects on the learning of simple and of complex skills, other factors appear to be relevant mainly for the learning of more complex skills. We interpret these apparently contradictory findings as suggesting that situations with low processing demands benefit from practice conditions that increase the load and challenge the performer, whereas practice conditions that result in extremely high load should benefit from conditions that reduce the load to more manageable levels. The findings reviewed here call into question the generalizability of results from studies using simple laboratory tasks to the learning of complex motor skills. They also demonstrate the need to use more complex skills in motor-learning research in order to gain further insights into the learning process.

In the past 30 years or so, research in motor learning has come a long way in describing and explaining how performance and learning of motor skills is affected by different variables. These include, for example, the distribution of practice (massed vs. distributed; see, e.g., Lee & Genovese, 1988, 1989), the feedback provided to the learner (timing, type, frequency; see, e.g., Salmoni, Schmidt, & Walter, 1984; Schmidt, 1991a), the organization of practice (practice variability, contextual interference; see, e.g., Magill & Hall, 1990; Shapiro & Schmidt, 1982), types of practice (e.g., physical, observational, mental; see, e.g., Jeannerod, 1994; McCullagh, Weiss, & Ross, 1989), and various guidance procedures (e.g., verbal, physical guidance; see, e.g., Hagman, 1983; Winstein, Pohl, & Lewthwaite, 1994). In general, however, the tasks used to examine the effects of these variables on learning have been relatively simple—often including only one degree of freedom, requiring comparatively small amounts of practice to reach performance asymptotes, and placing relatively modest demands on attention, memory, and/or processing capacity. Obviously, there are several advantages to using more basic tasks of the type typically used in the study of motor learning (e.g., ease and objectivity in measuring performance, savings in terms of money and other resources). Yet, if the goal is to understand motor skill learning in general and to provide recommendations for the training of motor skills in applied settings (e.g., in sports, music, or industry), it seems to be necessary to study the acquisition and learning of more "complex" skills that, at least initially, pose greater challenges to the cognitive capacity of the learner.

Defining movement or task complexity for a wide variety of motor tasks on a single task characteristic or movement outcome continuum is a difficult, if not impossible, challenge, for many practical and theoretical reasons. For example, movement complexity has been proposed to increase with increases in reaction time (RT; e.g., Henry & Rogers, 1964; Klapp, 1995), movement time (MT; e.g., Fitts, 1954), response errors/variability (e.g., Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979), or number of degrees of freedom (e.g., Bernstein, 1967). Although each of the continua is relatively effective in describing task complexity, when multiple tasks are carefully constructed along the continuum of interest, no one continuum is satisfactory in quantifying the complexity of the wide variety of motor tasks that have been investigated. For example, MT is effective in describing task difficulty for certain classes of simple aiming tasks in which, for example, movement amplitude and target width are varied but is not effective in quantifying differences in complexity between aiming movements and more continuous ski simulator or sta-

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bilometer tasks. Likewise, movement complexity tends to increase for reaching tasks as the number of degrees of freedom increases, but complexity may actually decrease for two-handed juggling, as compared with one-handed (cascade) juggling, even though the number of degrees of freedom is increased for the two-handed case. Thus, in the larger context, the determination of task complexity must take into consideration where a task fits on a number of continua, how the continua interact to fully define complexity, and ultimately, the demands placed on the memory and processing capacity of the learner.

This is complicated further if one considers that functional task complexity changes as a result of expertise. Presumably, this change is preceded by a concomitant reduction in memory and processing demands as performance becomes more automated. That is, as an individual performer develops expertise with a task, the functional complexity of the task decreases. This could be expressed in faster RTs (e.g., Adams, 1976) and MTs, smaller response errors, reduced attention demands (e.g., Schneider & Shiffrin, 1977), increased movement efficiency (e.g., Durand, Geoffroi, Varray, & Préfaut, 1994; Kahnemann, 1973), and either a decrease (freezing) or an increase (unfreezing) in the number of degrees of freedom (e.g., Vereijken, van Emmerik, Whiting, & Newell, 1992) utilized to produce the movement after experience with a task, as compared with initial trials of practice. The important point is that although task complexity is a multidimensional construct that is hard to quantify across a wide range of tasks, this quantification problem should not preclude making more qualitative judgments of task complexity, so that we could conclude with reasonable certainty that a ski simulator task, for example, that requires several days of practice to develop moderate levels of skill is initially more complex than typical barrier-knockdown tasks or sequential keypress tasks in which performance asymptotes are sometimes achieved in as little as 54 trials (e.g., Limons & Shea, 1988; J. B. Shea & Morgan, 1979; J. B. Shea & Titzer, 1993).

Thus, although an exact definition of complexity is not possible, for present purposes, we will judge tasks to be complex if they generally cannot be mastered in a single session, have several degrees of freedom, and perhaps tend to be ecologically valid. Tasks will be judged as simple if they have only one degree of freedom, can be mastered in a single practice session, and appear to be artificial. Although this portioning might not be perfect, it will be shown to be useful nonetheless.

Cognitive Effort and Information-Processing Demands

Several principles have emerged from the study of relatively simple skills in the last few years. On the basis of findings from a number of different paradigms, it has been suggested that practice conditions that promote additional cognitive effort (Lee, Swinnen, & Serrien, 1994) or require the learner to engage in additional information-processing activities that are critical for test performance (Schmidt & Bjork, 1992) are most effective for learning. For example, because a random practice order of different tasks exercises retrieval processes that later facilitate test performance—and therefore requires more effort than does blocked practice—performance at the time of the test is usually enhanced (for a review, see Magill & Hall, 1990). Similarly, making augmented feedback difficult to use—for example, by delaying it or by withholding it on some practice trials—has been argued to be beneficial for test performance because it forces learners to develop their own internal error-correction-and-detection mechanisms (for a review, see Schmidt, 1991a). Thus, adding an additional degree of "difficulty" for the learner during practice and thereby promoting greater effort and/or information-processing activities on his or her part is assumed to result in payoffs under "test" conditions.

Although this notion is intuitively appealing, the question is whether these and other principles, developed primarily through the study of simple laboratory skills, generalize to the learning of more complex skills, such as many skills required in real life. Consider a student driver, for example, who has to learn to coordinate the actions of the left foot depressing the clutch with those of the right foot on the gas pedal, those of the right arm shifting into the appropriate gears, and those of the left arm steering and activating the signal. (Similar difficulties are encountered by experienced drivers having to drive a British car in the U.K.!) Would learning be enhanced if the student driver practiced under conditions that required additional cognitive effort and additional information-processing activities? If so, should beginning drivers practice during the rush hour in a big city, where in addition to coordinating his or her limb movements, the driver is required to negotiate his or her way through traffic? Or, would not only performance, but also learning (as measured by later performance under test conditions) be facilitated if the novice driver practiced under conditions with little or no traffic, where the processing demands are more manageable? In other words, is it possible that complex skill learning would benefit from *reduced* task demands during practice, as opposed to the learning of simple skills, which seems to benefit from *increased* task demands?

For relatively simple skills, a rough movement representation may be developed within a few practice trials, and it is easy to see that a further refinement of the skill is dependent on the extent to which the learner is challenged by the practice conditions. On the other hand, the development of a movement representation for a more complex skill that requires the coordination of many degrees of freedom and may initially be stored as a series of relatively independent subcomponents typically takes considerably longer and inherently requires more effort and information-processing activities on the part of the learner. It is conceivable that introducing additional demands for the learner during this process is actually detrimental, rather than beneficial, because the additional demands compete with the essential processing activities for a limited amount of processing capacity during the learning process. Instead, complex skill learning might be enhanced by providing the learner with practice conditions that *facilitate* performance (at least until a relatively stable movement presentation is acquired). In addition to possible differential effects that some variables might have on simple versus complex skill learning, it is also possible that complex skills are sensitive to variables that are not particularly relevant for simple skills.

In this paper, we will try to assess what, if anything, the study of simple skills can tell us about the learning of complex skills. Although research using complex motor skills is still comparatively sparse, in the past few years an increasing number of studies have utilized more complex skills. In the first part of this paper, we will review variables that have been examined in the context of both simple and complex skill learning. These variables include the schedule of practice (contextual interference, CI), the feedback given to the learner, and the use of physical guidance. These factors indeed seem to have different effects, depending on the complexity of the skill, indicating that at least some of the principles that have been found for the acquisition of simple skills do not generalize very well to the learning of more complex skills. In the second part, we will review factors that seem to be particularly relevant for the learning of complex skills—that is, observation of and interaction between learners, and the learner's focus of attention. These findings also challenge the assumption that a complete understanding of motor-learning processes can be gained by using simple laboratory-type tasks (e.g., Adams, 1971). Rather, they suggest that research should systematically include more complex tasks to enhance our insights into these processes and to enable us to provide adequate recommendations for practical applications. Only when simple and complex skills are systematically studied can boundary conditions for sound motor-learning principles be established. In the final section, we attempt to provide a synopsis and to give an outline for future research.

PRACTICE VARIABLES HAVING DIFFERENTIAL EFFECTS ON SIMPLE AND COMPLEX SKILLS

This section focuses on variables that have been examined fairly extensively in the motor-learning research literature. However, most of these studies used rather simple tasks. Only recently have researchers begun to examine the effectiveness of such variables as CI, the frequency and organization of feedback, or physical guidance on the learning of more complex tasks.

Contextual Interference

J. B. Shea and Morgan (1979) were the first to demonstrate the CI effect for motor skill learning. In their study, participants had to learn three different versions of a barrier-knockdown task, with the order of barriers being different for each task. Practicing the tasks in a blocked order, in which all trials on one task were completed before the participant was switched to the next task (low CI), resulted in more effective performance during practice than did practicing the tasks in a random order (high CI). However, when learning was assessed in retention and transfer tests, the random-practice group demonstrated clearly superior performance to the blocked group.

Since the J. B. Shea and Morgan (1979) study, the learning advantages of random, as compared with blocked, practice have been replicated in numerous laboratory experiments. Several studies used multisegment tasks, similar to those in J. B. Shea and Morgan, and CI effects have been found independently of whether the task required the participants to produce the movement sequence as fast as possible (e.g., Gabriele, Hall, & Buckolz, 1987; Lee & Magill, 1983, Experiments 1 and 2; Limons & Shea, 1988; J. B. Shea & Zimny, 1983), to meet a certain overall movement time (e.g., Carnahan, Van Eerd, & Allard, 1990; Gabriele, Hall, & Lee, 1989; Gabriele, Lee, & Hall, 1991), or to produce certain segment times (e.g., Lee & Magill, 1983, Experiment 3; Lee, Wulf, & Schmidt, 1992; Sekiya, Magill, Sidaway, & Anderson, 1994; Wulf & Lee, 1993). Furthermore, learning advantages for random over blocked practice have been shown for very simple aiming tasks (Young, Cohen, & Husak, 1993), anticipation-timing tasks (e.g., Del Rey, 1982; Del Rey, Whitehurst, Wughalter, & Barnwell, 1983; Del Rey, Wughalter, & Carnes, 1987; Del Rey, Wughalter, & Whitehurst, 1982; Goode, 1986), movement patterning tasks (Sekiya, Magill, & Anderson, 1996; Wulf, 1992), and tracking tasks (Jelsma & Pieters, 1989; Jelsma & Van Merriënboer, 1989). Thus, the CI effect has proven to be a fairly robust phenomenon, at least for the learning of simple skills in laboratory situations.

To explain the CI phenomenon, several hypotheses have been put forward. The most prominent ones are the elaboration hypothesis of J. B. Shea and colleagues (J. B. Shea & Morgan, 1979; J. B. Shea & Zimny, 1983) and the forgetting or reconstruction hypothesis of Lee and Magill (1983, 1985). According to the *elaboration* hypothesis, random practice leads to more distinctive and elaborate memory representations than does blocked practice because participants use multiple and variable information-processing strategies. Since the different tasks to be learned reside together in working memory, they can be compared during practice (which is not possible under blocked conditions), increasing the level of distinctiveness. Also, the use of different encoding strategies supposedly leads to a more elaborate memorial representation than does the impoverished encoding under blocked conditions. The more distinctive and elaborate representation of the skill after random practice is assumed to be responsible for the more effective retention and transfer performance.

According to the *reconstruction* hypothesis (Lee & Magill, 1983, 1985), on the other hand, the CI created by random practice leads to forgetting of the action plan, or motor program (Magill & Hall, 1990), owing to the interference of the interspersed tasks. Random practice, therefore, necessitates repeated reconstructions of the motor program that are not necessary under blocked practice conditions, since the motor program is already in working memory. The repeated action plan reconstructions in random practice are supposed to be responsible for the learning advantages, as compared with blocked practice.

Other hypotheses have been suggested as well (J. B. Shea & Titzer, 1993; Wulf & Schmidt, 1994). Even though there is some support for all of the proposed hypotheses (for a review, see Magill & Hall, 1990), it is still unclear which explanation is the most viable. Also, none of the accounts makes differential predictions regarding the effectiveness of random versus blocked practice for simple versus complex skills. Yet, whereas the CI effect has been demonstrated fairly consistently for relatively simple laboratory tasks, this does not seem to be the case for more complex skills.

One study that found benefits of high-CI practice for the learning of a sport skill is a study by Smith and Davies (1995), who used the Pawlata kayak roll. Participants without prior experience in kayaking showed more effective retention (full roll) and transfer (half roll) if they had frequently alternated the direction of the roll during practice, as compared with participants who first completed half of the practice trials with the roll in their preferred direction and then performed the other half to the other side. Also, Wrisberg and colleagues (Wrisberg, 1991; Wrisberg & Liu, 1991) have found additional convincing evidence for the greater effectiveness of practice conditions that included frequent changes between tasks. In both studies, alternating different serves produced more effective learning than did blocked practice.

However, other studies using relatively complex tasks have yielded mixed results. For example, Tsutsui, Lee, and Hodges (1998) found beneficial effects of random practice for the learning of three patterns of a bimanual coordination task only if the patterns were practiced on different days (Experiment 2), but not if they were practiced on one day (Experiment 1) under blocked conditions. Goode and Magill (1986) had participants practice three types of serves in a blocked, a serial, or a random order. In retention and transfer tests, the random group tended to be more effective than the blocked group. However, these advantages were seen only for one serve and were significant in an interaction only when the superior performance of the blocked group on the last acquisition block was included. Bortoli, Robazza, Durigon, and Carra (1992), who examined the learning of volleyball skills (volley, bump, serve) under different CI conditions, also found only very limited support for enhanced learning through increased CI. There were no learning advantages (as measured by accuracy in hitting a target) of random or serial practice, as compared with blocked practice, in retention or transfer from a shorter distance. Only when transfer was required from a longer distance did random practice and serial practice with low interference produce higher accuracy scores than did blocked or serial practice with high interference.

Although the above-mentioned studies provide at least some evidence for the advantages of random practice for the learning of complex skills, there are other studies that call into question the effectiveness of random practice, especially for novice performers attempting to learn a complex movement pattern. In a study by Hebert, Landin, and Solmon (1996), undergraduate students with different skill levels (low skilled, high skilled) practiced forehand and backhand tennis groundstrokes under either a blocked or an alternating schedule. Whereas there was no difference in the posttest score for high-skilled learners, the blocked schedule was more advantageous than the alternating schedule for low-skilled learners.

Several studies with children add support for the view that random practice apparently can be too demanding and, therefore, less effective for the learning of complex skills if performers are relatively inexperienced. For example, for teaching ninth-grade students different volleyball skills (overhead set, forearm pass, serve), French, Rink, and Werner (1990) found no differential effectiveness of blocked, random, or mixed random–blocked practice schedules. Farrow and Maschette (1997) had 8–9 year olds and 10–12 year olds practice the tennis forehand groundstroke with the preferred and the nonpreferred hands. In a posttest, random practice led to better preferred groundstrokes than did blocked practice in the older group; however, blocked practice was more effective than random practice for the younger group. In addition, blocked practice proved to be generally more effective for performing the nonpreferred forehand. Similarly, Pinto-Zipp and Gentile (1995) found that blocked practice of a Frisbee-throwing task benefited young children (5–6 years), whereas random practice was better for adults. In fact, they found that when only limited amounts of practice were provided, both adults and children learned more via blocked than via random practice. Pigott and Shapiro (1984) had children 7 years, 6 months of age practice throwing bean bags of different weights at a target. They found that practice conditions with a medium level of CI (random–blocked practice) was most effective and, in contrast to random practice, produced significantly better learning than did blocked practice. Finally, Al-Mustafa (1989) had 1-, 5-, 7-, 11-, and 19-year-old participants practice a throwing task under random or blocked conditions. In his experiment, random practice facilitated learning for older children and adults; however, younger children benefited from blocked practice. In a second experiment, Al-Mustafa found that 7-year-old children with related movement experience achieved better retention results after random practice.

Overall, these results seem to indicate that, when the tasks are more difficult because of high attention, memory, and/or motor demands (or when learners are relatively inexperienced), random practice may *overload* the system and thus disrupt the potential benefits of random practice. Recently, Albaret and Thon (1999) directly tested the hypothesis that the complexity of the task could modulate the CI effect. They reasoned that complex tasks are accompanied by relatively high memory demands that obscure the normally beneficial effects of intertask interference. In order to manipulate task difficulty, a set of drawing tasks was constructed that differed in terms of the number of line segments. The results indicated a clear advantage of random practice for the simplest version of the tasks on delayed retention and transfer tests. However, the effect was systematically reduced as the number of segments was increased and was even reversed (blocked practice better than random), albeit not significantly, for the most difficult tasks.

J. B. Shea and colleagues (e.g., J. B. Shea & Morgan, 1979; J. B. Shea & Zimny, 1983) proposed that one of the major benefits of random practice arises from intertask elaboration resulting from multiple items, simultaneously held in working memory, being compared and contrasted. However, complex tasks, presumably requiring considerably more memory capacity per task, may exceed the capacity of the performer. This may be especially true early in practice, where a single complex task may be initially stored as a series of subcomponents (e.g., Povel & Collard, 1982). In addition, J. B. Shea and Zimny concede that in more complex tasks, there may be sufficient intratask interference (e.g., Battig, 1972) arising from the elaboration relative to the movement subcomponents of a single task to promote learning, nullifying the potential advantage of intertask interference. Consistent with the notion of overloading working memory, Wright, Li, and Whitacre (1992; also see Lee, Wishart, Cunningham, & Carnahan, 1997) found that additional processing disrupted learning under random-practice conditions but had positive effects under blocked conditions.

In addition, a number of recent experiments (e.g., Lai & Shea, 1998, 1999; Lai, Shea, Wulf, & Wright, 2000; C. H. Shea, Lai, Wright, Immink, & Black, 2001; Whitacre & Shea, 2000) consistently found relative timing advantages for constant and blocked practice, relative to serial and random practice, directly opposite the typical CI effect. These experiments have used what, on the surface, appear to be relatively simple tasks, which in other experiments (minus the relative timing demands) have produced typical CI effects. The difference is that participants have been asked in these experiments to attempt not only a goal movement outcome (as in most CI experiments), but also to produce a specific relative force and/or timing pattern. The additional demands of balancing relative and absolute demands apparently significantly increase the complexity of the task and, also, the effect of CI. In fact, when the relative timing pattern required is greatly simplified by making the segment requirements equal across the task (Wright & Shea, 2001), the advantages of blocked, relative to random, practice on relative timing learning are lost.

Overall, the picture that emerges from the studies reviewed above seems to show that random practice is usually more effective than blocked practice when it comes to the learning of simple skills, for which the memory demands are relatively low, and/or when participants are experienced to the extent that they have functionally reduced the demands on memory (Hall, Domingues, & Cavazos, 1994). For the learning of more complex skills for which memory and processing demands are high, blocked practice might be more effective, at least early in the learning process. Carr and Shepherd (2000) also extended this notion to neurological and some orthopedic patients, who like children and novices, often have difficulty controlling the intersegmental dynamics inherent in complex whole-body tasks. Support for this view also comes from a study by C. H. Shea, Kohl, and Indermill (1990), in which blocked practice was more effective for the learning of a rapid force production task when practice was limited to 50 trials. However, with increasing amounts of practice trials (200, 400), random practice produced more effective retention performance than did blocked practice, suggesting that a certain level of experience is required for random practice to become more effective than blocked practice.

This position can be reconciled with both the elaboration and the reconstruction accounts for the CI effect. For example, when complex tasks are first practiced, short-term memory may be overloaded, preventing or at least limiting processing (elaboration) of the various tasks. Alternatively, full reconstruction may be difficult from trial to trial. In either case, the development of memory representations, or motor programs, for the different tasks would be degraded, since random practice adds to the already high processing loads. The intratask interference inherent in complex tasks may be sufficient for effective learning under blocked conditions, at least in the early phases of practice. Once the movements become more automated—and therefore less difficult for the performer—introducing further challenges by varying the practice context might provide the necessary stimuli for continued learning.

Feedback

One of the most important variables in the motor-learning process is the feedback provided to the learner attempting to acquire a new motor skill. Consequently, this variable has received a great amount of interest in the research literature. In this section, we will review findings related to the frequency of feedback and the organization of feedback about different task components.

Feedback frequency. A number of studies, mainly using relatively simple tasks, have demonstrated that reducing the proportion of trials for which augmented feedback (knowledge of results, knowledge of performance) is provided can result in more effective learning than does giving feedback after every single trial (e.g., Nicholson & Schmidt, 1991; Weeks & Kordus, 1998; Winstein & Schmidt, 1990; Wulf, Lee, & Schmidt, 1994; Wulf & Schmidt, 1989; Wulf, Schmidt, & Deubel, 1993; Wulf, Shea, & Rice, 1996; however, see Lai & Shea, 1998). For example, using a lever-patterning task, Winstein and Schmidt found that reducing the feedback frequency to 50% of the trials was more beneficial for the learning of this task than giving 100% feedback. Furthermore, delaying the feedback for a few seconds has been found to produce more effective learning than does giving feedback immediately after or even concurrently with the movement (e.g., Schmidt & Wulf, 1997; Swinnen, Schmidt, Nicholson, & Shapiro, 1990; Vander Linden, Cauraugh, & Greene, 1993). In particular, concurrent feedback typically has strong performance-enhancing effects during practice, but results in clear performance decrements, relative to postresponse feedback, when it is withdrawn in retention or transfer tests (Schmidt & Wulf, 1997; Vander Linden et al., 1993; Winstein et al., 1996).

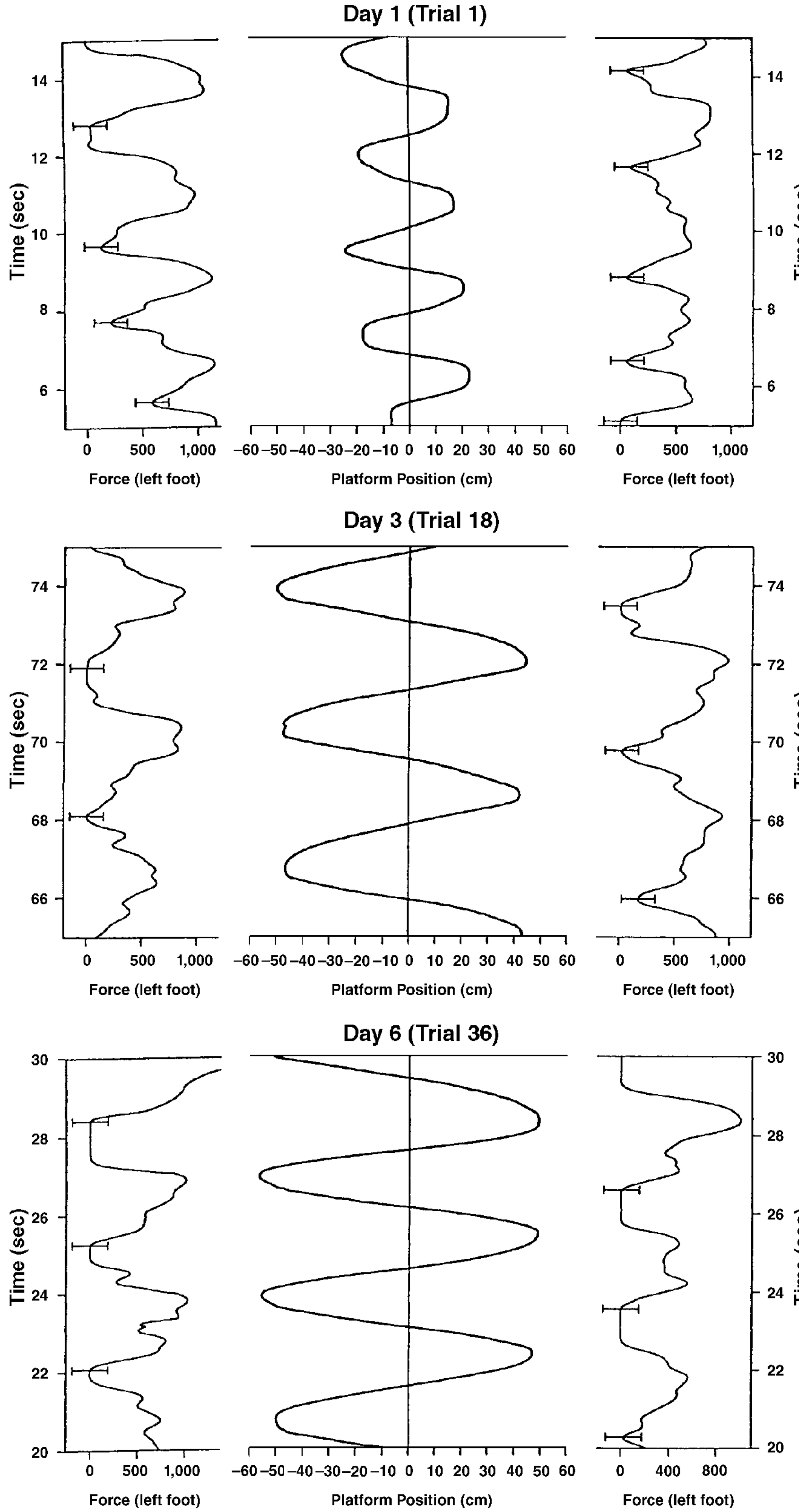
Some of these findings appear to have parallels in the literature on animal conditioning. In this work, partial reinforcement has been shown to slow acquisition but also to maintain learning for much longer than continuous reinforcement does. The reason for this is seen mainly to lie in the fact that partial reinforcement tends to simulate extinction conditions (e.g., Tarpy, 1982, chap. 7). However, as Winstein and Schmidt (1990; see also Wulf & Schmidt, 1989) have pointed out, one set of findings that argues against such an explanation for human learning is that beneficial learning effects of reduced feedback are seen not only in no-feedback retention tests, but also in 100% feedback retention tests. Such a finding would seem unlikely in animal learning. Furthermore, immediate reinforcement is more effective than delayed reinforcement in animal learning, but this is not the case for skill learning in humans. This suggests that although the principles underlying animal reinforcement and feedback in humans have some similarities, they show some important differences as well.

The degrading effects of frequent and immediate feedback on delayed retention and transfer tests found in human learning are typically explained with the *guidance hypothesis* (Salmoni et al., 1984). According to this hypothesis, feedback has positive effects, such as guiding the learner to the correct response; however, frequent feedback is also argued to have several side effects that degrade learning. For example, learners seem to become too dependent on the information provided by the augmented feedback and neglect the processing of intrinsic (e.g., proprioceptive) feedback, which they will have to rely on when the additional information is no longer available (i.e., in no-feedback retention or transfer). In addition to making learners dependent on it, frequent feedback has been shown to make movement production quite variable, presumably preventing the learner from developing a stable movement representation (Lai & Shea, 1998; Wulf & Schmidt, 1994; see also Schmidt, 1991a). Finally, feedback has been argued to work proactively by facilitating next-response planning and retrieval. In this sense, frequent feedback might provide too much facilitation in the planning of the subsequent response, thereby reducing the participant's need to perform memory retrieval operations thought to be critical for learning (Wulf & Schmidt, 1994).

Although the learning of simple skills seems to benefit from reducing or delaying the augmented feedback (although this effect appears to be stronger for variable practice conditions; see Lai & Shea, 1998), there is evidence to suggest that more frequent feedback might be required for the learning of complex skills. Some support for this notion comes from studies on summary feedback (or summary knowledge of results), where feedback about each trial is given only after a certain number of trials have been completed. Whereas in experiments using relatively simple tasks, the largest summary feedback length proved to be the most effective for learning (e.g., a summary of 16 trials in Gable, Shea, & Wright, 1991; 20 trials in Lavery, 1962; 15 trials in Schmidt, Young, Swinnen, & Shapiro, 1989), Schmidt, Lange, and Young (1990) showed that the optimal number of summary trials for a more complex simulated batting task was lower than those found for more simple tasks. In this case, a summary of 5 trials was more beneficial than longer (15) or shorter (1) feedback summaries. Also, Yao, Fischman, and Wang (1994) found that both summary feedback and average feedback (where an average error or performance score is provided after a set of trials) about 5-trial blocks was more advantageous for learning than was feedback about 15-trial blocks or every-trial feedback. Finally, Guadagnoli, Dornier, and Tandy (1996) directly demonstrated that task complexity, as well as task-related experience, interacted with the optimal number of trials summarized. That is, whereas relatively long feedback summaries benefited the learning of a relatively simple striking task for both novice and experienced participants, as well as the learning of a more complex double-striking task for experienced participants, single-trial feedback was more effective than longer feedback summaries for novices trying to learn a complex task.

Presumably, the most complex task that has been used to examine the effects of a reduced feedback frequency is the ski simulator task (Wulf, Shea, & Matschiner, 1998, Experiment 2). The ski simulator consists of two bowed rails and a platform on wheels that is attached to the ends of the apparatus by elastic rubber belts (see Figure 1). If the platform is displaced, the rubber belts pull the platform back to its center position. The platform can be made to move sideways on the rails by exerting force on it. The goal of the performer standing on the platform is to make oscillatory, slalom-type movements, with the goal being to produce the largest possible amplitudes (and sometimes frequency). Similar to many sport skills, this task requires extensive practice, and learners usually continue to show improvements in performance across several days (e.g., den Brinker & van Hekken, 1982; Durand et al., 1994; Vereijken, 1991; Wulf, Shea, & Matschiner, 1998).

Wulf, Shea, and Matschiner (1998, Experiment 2) provided learners on the ski simulator with feedback about a performance measure, the so-called relative force onset,


Day 1 (Trial 1)

Day 3 (Trial 18)

Day 6 (Trial 36)

Figure 1. Platform position and force curves of the left and right feet for 1 participant on Days 1 (top), 3 (middle), and 6 (bottom) in the Wulf, Shea, and Matschiner (1998) study. Force onsets are indicated on the force curves; as can be seen, the force onsets occurred later and later in the movement cycle (e.g., between two successive reversals of the platform) across practice.

that was found to correlate with performance in terms of movement amplitude in their Experiment 1. That is, experts on this task not only produced larger amplitudes, but also showed later relative force onsets than did beginners. The relative force onset is viewed as a measure of movement efficiency. Basically, the force onset indicates when the performer shifts his or her weight from one foot to the other. More specifically, it is the point in time at which the performer shifts his or her weight to the left foot while moving to the right and vice versa. Optimally, when moving, say, to the right side, the body weight should only be on the right ("outer") leg until the reversal point is reached. Beginners, however, tend to shift their weight relatively early—for example, when the platform passes the center of the apparatus. With an increased amount of practice, the force onset occurs later and later in the movement cycle and, for some performers, eventually coincides with the platform reversal. (The *relative* force onset is the force onset in relation to the overall duration of the movement cycle.)

In the Wulf, Shea, and Matschiner (1998, Experiment 2) study, beginners were provided with feedback about force onset and were instructed to try to delay the force onset until they reached the reversal point. The feedback was presented on an oscilloscope concurrently with and for the whole duration of a 90-sec trial. Whereas one group of participants received feedback on all practice trials that were performed on 2 consecutive days (100% feedback), for another group the feedback was faded, with the average feedback frequency being 50%. In addition, there was a control group without feedback. In delayed retention, all the groups showed very similar performances in terms of relative force onset on the first of 10 no-feedback retention trials. However, the group that had received the most feedback (100%) during practice showed a clear performance improvement across trials, whereas the 50% feedback group showed no such performance gains, and the control group even demonstrated a performance decrement. By the end of the retention test, the participants in the 100% group produced even later force onsets than they did toward the end of the practice phase with feedback present. Furthermore, only the 100% group was significantly more effective than the control group, whereas the 50% group did not differ significantly from either group.

Thus, there was no indication that the 100% feedback participants developed a dependency on the feedback that reduced the learning effectiveness of this condition. Rather, it seems that the participants in the 100% feedback group developed a more effective error-detection-and-correction mechanism (e.g., Salmoni et al., 1984; Schmidt, 1991a), as compared with the 50% feedback and no-feedback (control) conditions, which enabled them to demonstrate further performance improvements even in the absence of feedback. Thus, contrary to studies that used more simple tasks in which reducing the relative feedback frequency was more beneficial for learning than was providing learners with feedback after or during every practice trial (e.g., Schmidt & Wulf, 1997; Winstein & Schmidt, 1990; Wulf & Schmidt, 1989; Wulf et al., 1993), the learning of this more complex task was enhanced by 100% feedback. Interestingly, this advantage occurred even though the feedback given in the Wulf, Shea, and Matschiner (1998) study was continuous and concurrent. At least for the learning of simple skills, concurrent feedback seems to produce an even stronger dependency on it than postresponse feedback after each trial does (Park, Shea, & Wright, 2000; Schmidt & Wulf, 1997; Vander Linden et al., 1993; Winstein et al., 1996). Since these dependency effects should be attenuated by a reduced feedback frequency, one might have expected a learning advantage for the 50% feedback condition. This was not the case for this more complex task, however.

In a recent study that required the learning of a complex bimanual coordination task, Swinnen, Lee, Verschueren, Serrien, and Bogaerds (1997) also found that continuous, augmented visual feedback enhanced performance and learning. Participants learning to produce cyclical arm flexion and extension movements with a phase offset of 90°, demonstrated more effective performance in acquisition and transfer if they received augmented visual information during practice, as compared with reduced feedback and normal vision practice conditions. That is, providing learners with frequent augmented feedback not only facilitated acquisition performance, but also enhanced learning, as measured by various transfer tests—irrespective of the feedback conditions experienced in these tests. This study provides another example of the beneficial effects of frequent feedback for complex motor skill learning.

Thus, it seems that, in contrast to simple skill learning, the learning of more complex motor skills benefits from relatively high feedback frequencies (at least until a certain level of experience is reached). This interpretation is in line with summary knowledge of results studies showing that the optimal number of trials summarized decreases with more complex tasks (e.g., Schmidt et al., 1990; Schmidt et al., 1989; Yao et al., 1994) and is especially in line with the findings and reasoning of Guadagnoli et al. (1996), who demonstrated an interaction between task complexity or task-related experience and optimal summary-KR length. Another question related to the effectiveness of feedback, which seems to be of particular importance for the learning of complex skills, is how feedback about different components of the task should be organized. This issue will be addressed in the following section.

Feedback organization. Complex motor skills usually require the spatial and temporal coordination of various submovements. This raises the question of how feedback should be organized in order to enhance learning: Should one concentrate on one aspect at a time, or should the movement feature that feedback is given about be changed more frequently? Perhaps owing to the predominant use of relatively simple skills, which often have only one overall goal (e.g., a temporal or spatial target) and which therefore do not lend themselves to examinations of feedback organization effects, relatively little research has been done to examine this question. Lee et al. (Lee & Carnahan, 1990;

Swanson & Lee, 1992), however, used a task that required participants to knock down a series of barriers, with certain goal MTs being prescribed for the different segments. After each trial, feedback was given about one of the movement segments. However, the order of segments that received feedback was different for different groups. Whereas for one group of participants this order was randomized, another group received feedback about the different segments in blocks of trials. In (immediate) no-feedback retention tests, the random feedback organization turned out to be more effective than the blocked organization. Lee and Carnahan argued that a blocked feedback schedule might result in less effective learning than a random schedule because it focuses the learners' attention on one part of the task and causes them to neglect the other parts or its integration into the whole action.

Wulf et al. (Wulf & Bühner, 1996; Wulf, Hörger, & Shea, 1999) examined the generalizability of these findings to the learning of the more complex ski simulator task. Similar to the study by Wulf, Shea, and Matschiner (1998, Experiment 2), feedback was provided about the forces exerted by each foot on the platform, and learners were instructed to try to delay the force onset of the inner foot until the reversal of the platform. In the Wulf, Shea, and Matschiner experiment, feedback was given for one foot at a time, but the foot that the feedback referred to was switched on consecutive trials; that is, feedback was provided in a serial order. In a first study to examine whether constantly changing the component receiving feedback is indeed optimal for the learning of this more complex task or whether a blocked schedule would be more effective in this case, Wulf and Bühner provided learners with 2 days of practice on the ski simulator. Feedback about the forces produced by each foot was presented in either a serial or a blocked order. Whereas the foot receiving feedback was switched on each practice trial for the serial feedback group, under blocked feedback conditions feedback was given for one foot per day. After 2 days of practice, the participants performed a no-feedback retention test on Day 3. In this retention test, the blocked feedback group demonstrated relative force onsets that were significantly later than those of the serial feedback group. That is, the blocked feedback order was more effective for the learning of a delayed force onset than was serial feedback.

These findings provided some preliminary evidence that, contrary to what has been found for the learning of a relatively simple skill (Lee & Carnahan, 1990; Swanson & Lee, 1992), a frequent change in the aspect of the task that receives feedback might not be advantageous for the learning of more complex skills. It is conceivable that serial or random feedback is too demanding if the task to be learned is relatively difficult, leading to the learning decrements seen in that study. However, it is also possible that with more practice—and decreasing attentional demands—serial (or random) feedback might eventually be beneficial for complex skill learning as well (see C. H. Shea et al., 1990). In a follow-up experiment, Wulf, Hörger, and Shea (1999) therefore provided learners with twice as many practice trials on the ski simulator as Wulf and Bühner (1996) had used—that is, 4 days of practice with 10 trials per day. One question in this study was whether the effectiveness of serial versus blocked feedback would interact with the amount of practice, so that blocked feedback would be more beneficial early in practice, but less beneficial later in practice, as compared with serial feedback. For this reason, no-feedback retention trials were performed at the beginning of each practice day. In addition, there was a retention test on Day 5. However, even with relatively extensive practice on this task, no advantages were found for serial feedback (see Figure 2). In fact, the blocked feedback group (which was given feedback about one foot on Days 1 and 3 and about the other foot on Days 2 and 4) produced consistently larger movement amplitudes than did the serial feedback group throughout the practice phase, as well as in all the retention tests. In this experiment, the beneficial effects of blocked practice were seen in amplitude, whereas there were no significant group differences in force onset (even though feedback was given about force onset, as in Wulf & Bühner, 1996), presumably because the instructions put more emphasis on the overall goal of the task—that is, the production of large amplitudes. At any rate, the results replicated the findings of Wulf and Bühner in demonstrating that blocked feedback was clearly more effective for the learning of this complex task.

Thus, even with considerable amounts of practice, the serial feedback condition—in which the participant's attention was switched on every trial between focusing on delaying the force onset of the left foot while moving to the right and focusing on delaying the force onset of the right foot while moving to the left—might have been too demanding and, perhaps, initially confusing and, therefore, resulted in degraded learning, relative to blocked feedback. Informal interviews at the end of the experiment confirmed that the serial feedback participants found this type of feedback to be very attention demanding. The additional attention demands directed at translating the force onset display information into action seemed to detract from the production of large movement amplitudes, which was the ultimate goal of the task. Under blocked feedback conditions, on the other hand, the learners could concentrate on one side/foot on each day, making practice less demanding and actually benefiting the learning of this complex skill.

Summary. Overall, the studies in which the effects of feedback frequency (Wulf, Shea, & Matschiner, 1998) and feedback organization (Wulf & Bühner, 1996; Wulf, Hörger, & Shea, 1999) on the learning of a complex task, such as the ski simulator task, were examined demonstrate that the findings derived from simple-task learning studies do not generalize very well to complex skill learning. In contrast to the simple laboratory tasks used in many studies, reducing relative feedback frequency did not enhance learning of the ski simulator task. In fact, providing concurrent feedback on 100% of the practice trials turned out to be most effective for learning. This suggests that

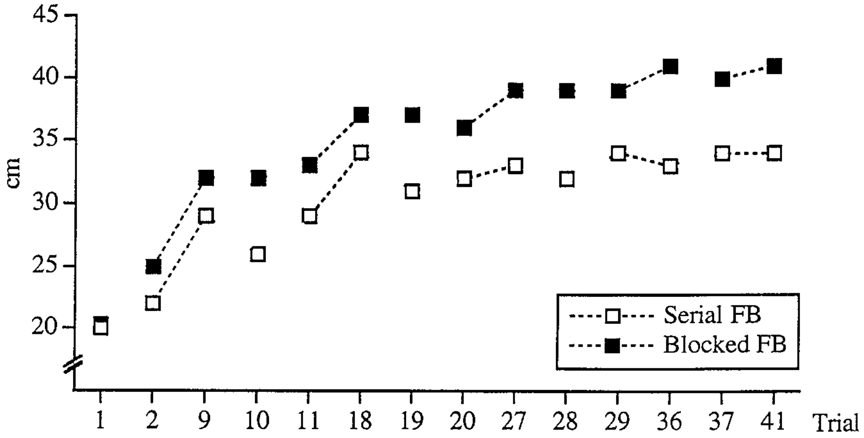


Figure 2. Movement amplitudes of the blocked and serial feedback (FB) groups on the pretest (Trial 1), during practice (Trials 2, 9, 11, 18, 20, 27, 29, 36), and on the no-feedback retention tests of Day 2 (Trial 10), Day 3 (Trial 19), Day 4 (Trial 28), and Day 5 (Trials 37–41) in the Wulf, Hörger, and Shea (1999) study. Blocked feedback about force onset facilitated the production of large movement amplitudes throughout practice and on all retention tests.

more feedback might be required to optimize complex skill learning. Furthermore, contrary to simple skill learning, concentrating the feedback on one task component at a time (blocked feedback) was found to be more beneficial for the learning of the ski simulator task than were frequent changes in the component about which feedback was provided (serial feedback). Together, these results suggest that whereas the learning of simple tasks might be enhanced by making practice more "difficult" or challenging for the learner (e.g., by reducing feedback frequency or providing serial/random feedback), the learning of complex skills might not benefit and might even be degraded by increasing the demands imposed on the learner. This is in line with the notion that, in contrast to simple skills, the learning of complex skills—with inherently high attentional, memory, or control demands—can be facilitated by providing the learner with relatively frequent feedback. It should also be noted, however, that feedback in complex tasks is generally not as prescriptive as it often is in many of the simple tasks that have been used in this context. In complex tasks, there are often different components that have to be coordinated to produce skilled performance, making it much more difficult for a single feedback measure to be truly prescriptive. In attempts to improve performance, the learner has to rely on sources of intrinsic feedback. Thus, the likelihood of the learner's becoming dependent on extrinsic feedback and neglecting the processing of intrinsic feedback is reduced, as compared with the learning of simple skills. That is, the negative effects thought to be associated with the guidance provided by frequent feedback seem to be reduced.

Physical Assistance

A form of guidance that seems to be even stronger than the guidance provided by feedback is physical guidance. In the laboratory, this is realized, for example, by moving the performer's limb to a target position (e.g., Holding & Macrae, 1964; Kelso, 1977) or by using a mechanical stop to indicate the target position (e.g., Hagman, 1983). Hagman and Winstein et al. (1994) examined the effects of physical guidance on the learning of positioning movements. In both studies, reducing the proportion of *presentation* trials, in which performers were presented with the mechanical stop, produced more effective learning, as assessed by retention or transfer tests without the stop, than did a relatively high proportion of presentation trials. Similar to the effects of high feedback frequencies, these results have also been viewed as support for the guidance notion, according to which the learner becomes dependent on the guidance and, therefore, demonstrates less effective learning when the guidance is removed. In fact, Winstein et al. (1994) showed that physical guidance had effects on learning similar to those of feedback about the movement outcome.

The use of physical guidance procedures can also be seen in many sport situations—for example, when a gymnast learning a new stunt is spotted by a coach or when a child learning to swim is provided with a flotation device. These procedures differ from those used in the abovementioned studies, however, in that they are less prescriptive. Although they provide support for the learner and thereby facilitate the achievement of the movement goal, the learner has more freedom for exploratory activities. Therefore, physical *assistance* might be a more appropriate term for such cases. Even though guidance techniques such as these had for a long time been regarded as effective means in teaching motor skills (e.g., Holding, 1969; Holding & Macrae, 1964, 1966), the newer findings regarding the effects of guidance on motor learning cast doubts on their effectiveness for learning (e.g., Salmoni et al., 1984). As Schmidt (1988, 1991b; Schmidt & Wrisberg, 2000) points out, the benefits of (physical) guidance seem to be mainly temporary in nature. Guidance often has strong performance-enhancing effects during practice, when it is present; yet when it is withdrawn in retention or transfer tests, performance is often less effective than that of learners who practiced the task without or with less guidance. Schmidt (1991b; see also Schmidt & Wrisberg, 2000) therefore recommended that physical guidance be used only sparely in the teaching of sport skills, in order to avoid the detrimental effects on learning that seem to be associated with too much guidance.

Very few studies have examined the effectiveness of physical guidance or assistance on the learning of more complex motor skills, however. In a series of experiments, Wulf and colleagues (Wulf & Shea, 1997, 1998; Wulf, Shea, & Whitacre, 1998) studied the effects of physical assistance devices on the learning of balancing tasks. In these studies, participants learning to maintain their balance on the stabilometer (Wulf & Shea, 1997, 1998; Wulf, Shea, & Whitacre, 1998) or to produce oscillatory movements on the ski simulator (Wulf, Shea, & Whitacre, 1998) were or were not provided with a pair of (ski) poles. The use of poles, which are placed on the floor in front of the apparatus, facilitates performance by providing a larger base of support. Thus, the poles serve a function similar to that of, for example, training wheels on children's bicycles or the support provided by a parent in ice-skating or by a physical therapist to a patient who is learning to walk again. That is, the physical assistance helps to guide the performer to the intended goal. Even though the guidance provided by a mechanical stop in a positioning task might provide more prescriptive information than the assistance provided by the ski poles (or similar devices in more real-world settings), the ski poles also greatly facilitate the achievement of the task goal—that is, the production of large movement amplitudes. The physical assistance provided by the poles is therefore comparable to assisted devices that are often used in real-world settings, where complex skills are being taught.

On the basis of previous findings (Hagman, 1983; Winstein et al., 1994) and reasoning (e.g., Schmidt, 1991a, 1991b), one would expect learning advantages for unassisted practice conditions (without poles), particularly as compared with conditions with 100% physical assistance during practice, since these participants have more opportunity to practice the relevant aspects of the task (e.g., maintaining balance or applying force to the ski simulator platform at the appropriate time). Even though physical assistance should enhance performance during practice, participants practicing with poles might bypass some of the processing that would be required for effective performance when the poles are removed and, as a result, show less effective learning (Schmidt, 1991a, 1991b). Also, from a specificity point of view (e.g., Henry, 1968), according to which learning is specific to the conditions encountered during practice, learners practicing without poles have a clear advantage over those practicing with poles, since their practice conditions are identical to the conditions encountered in retention. On the other hand, it is also conceivable that, for more complex tasks in which the memory and information-processing demands are high, the physical assistance provided by the poles could reduce the demands to a more manageable level, thereby helping learners to get a feel for the goal movement or helping them figure out how to produce an effective coordination pattern. This may not be possible early in practice, where the immediate goal is simply to try not to fall off the device.

Wulf, Shea, and Whitacre (1998, Experiment 1) examined the effects of physical assistance devices on learning to perform slalom-type movements on the ski simulator. Whereas one group of learners practiced the task with ski poles, another group practiced without poles. Both groups performed immediate retention tests without poles at the end of each of the 2 days of practice, as well as a delayed retention test on Day 3. As one would expect, the use of poles clearly facilitated performance. That is, the pole group produced larger amplitudes than did the group that practiced without poles throughout the acquisition phase. In addition, the pole group demonstrated later relative force onsets (see Figure 3), indicating that the poles also facilitated the production of a more efficient movement pattern (Wulf, Shea, & Matschiner, 1998). More important, though, when the poles were removed in retention, the group that had practiced with the poles showed no performance decrements in amplitude or force onset. Both groups had very similar amplitudes in the delayed retention test, and even more interesting, the pole group demonstrated superior learning with regard to relative force onset. That is, the participants who had practiced with the poles showed force onsets under no-pole conditions that were similar to those produced during practice with the poles. Thus, the benefits in force onset provided by the poles during practice were not only temporary effects. Rather, these benefits transferred to a situation in which no poles could be used, and they were relatively permanent in nature; that is, the poles enhanced the learning of a more efficient movement pattern, relative to practice without poles.

These results are not in line with guidance (e.g., Schmidt, 1991a, 1991b; Schmidt & Wrisberg, 2000) or specificity-of-learning notions (e.g., Henry, 1968), according to which unguided practice should have been more effective for learning than was practice with physical guidance or assistance. On the ski simulator, the poles might have enabled learners to experience (consciously or unconsciously) that it is more effective to shift the weight from the outer to the inner foot relatively late—that is, to delay the force onset of the inner foot. This experience provided by the poles served to shorten the learning process and enabled the learners to reach a given level of performance in less time. These results again suggest that there may be limitations to the generalizability of findings from studies using typical laboratory tasks with few degrees of freedom. For complex movements with many degrees of freedom, such as those encountered in many sports situations, there might actually be advantages to using physical assistance procedures, corroborating the view that complex skill

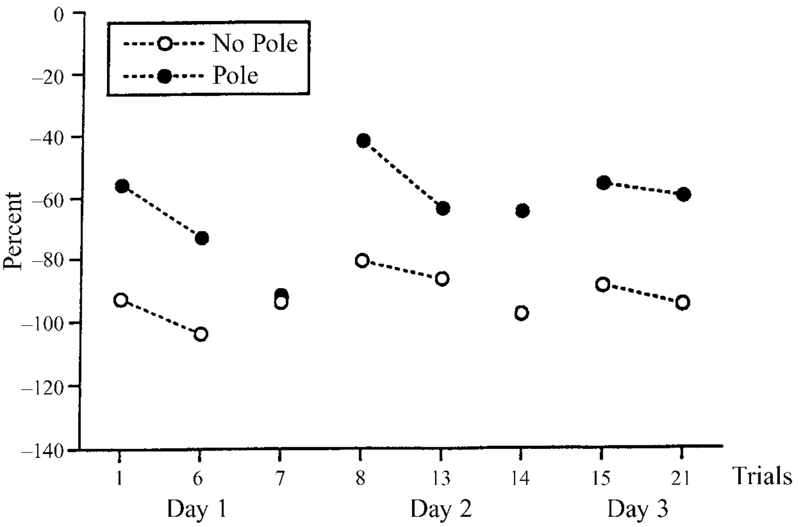


Figure 3. Relative force onsets of the pole and no-pole groups during practice (Trials 1–6 and 8–13) and in the immediate (Trials 7 and 14) and delayed retention tests (Trials 15–21) without poles in Experiment 1 of Wulf, Shea, and Whitacre (1998). The use of the poles facilitated the production of late force onsets not only during practice, but also in delayed retention.

learning benefits from reducing the demands imposed on the learner.

However, there might be other factors (besides the complexity of the task) that determine to what extent physical guidance or assistance is beneficial or detrimental to learning. For example, using the stabilometer task—that is, a dynamic balance task that requires performers to maintain their balance on a wooden board pivoting over a fulcrum to the left and right—Wulf and Shea (1997, 1998) found that providing learners with poles was not advantageous for learning. Independent of whether the task was to keep the platform in a horizontal position (Wulf & Shea, 1997) or to continuously move the platform so that its position coincided with a template presented on a computer screen (Wulf & Shea, 1998), practice with poles did not enhance learning. Even though the poles again facilitated performance during practice, participants who had practiced without the poles were more effective in delayed no-pole retention tests. It is conceivable that physical assistance is conducive to learning to the extent that it allows the learner to explore the "perceptual–motor workspace" (Newell, 1991). On the ski simulator task, the poles enabled learners to produce a movement pattern—that is, large movement amplitudes—that otherwise they would not have experienced until much later in practice or, perhaps, not at all. In addition, through the use of the poles, learners presumably experienced that a late force onset is more effective. That is, in this case, the poles might have facilitated the learner's search for the optimal solution of the motor problem. On the stabilometer task, on the other hand, the poles might have prevented the performer from exploring the perceptual–motor workspace. For example, because of the additional support provided by the poles, learners were able to keep the stabilometer platform "on target" (e.g., in the horizontal) for most of the time. This way, however, they did not experience larger deviations from the goal and, consequently, did not learn how to reduce the deviations without the help of the poles. More research is needed, however, to determine under what conditions the learning of complex motor skills is degraded or enhanced by physical guidance.

VARIABLES INFLUENCING MAINLY COMPLEX SKILL LEARNING

As the previous sections have shown, learning principles derived from the study of simple skills are not necessarily generalizable to the learning of more complex skills. Therefore, in order to understand the processes underlying the learning of complex motor skills and to be able to give recommendations for the teaching of these skills, it seems important to examine directly the learning of more complex skills. In addition, there might be other advantages to using more complex skills in motor-learning research. For example, some principles or phenomena that could be relevant for the learning of complex skills might be less powerful or might not show up in tasks such as those typically used in the laboratory. One characteristic of complex motor skills that is difficult to simulate with simple tasks is that the performer can direct his or her attention to various aspects of the task. This poses a challenge not only for the practitioner who wants to optimize training by directing the performer's attention, through instructions or feedback, to the relevant aspects of the task, but also for the researcher who wants to understand the role and function of attentional processes in skill acquisition. Another variable that, for various reasons, seems to have great potential for enhancing complex skill learning is observational practice. Whereas having learners observe another performer has yielded mixed results for the learning of simple skills, it seems to have clear benefits for more complex skills. In the subsequent sections, we will review the effectiveness of these factors in more detail.

Attentional Focus

A number of studies have demonstrated that the performer's focus of attention can have a decisive influence on performance and learning. Whereas most of these studies manipulated the learner's attention via instructions, more recent work has also examined the effectiveness of different attentional foci induced by the feedback given to the learner.

Instructions. In a series of studies, Wulf and her colleagues (Wulf, Höß, & Prinz, 1998; Wulf, Lauterbach, & Toole, 1999; Wulf, Shea, & Park, 2001) manipulated the learners' focus of attention by giving them different instructions. These studies were stimulated by a previous study, which showed that giving learners instructions that could be assumed to enhance the learning process is not necessarily beneficial for the performance and learning of a complex skill (Wulf & Weigelt, 1997). In the Wulf and Weigelt experiment, performers attempting to produce large-amplitude movements on the ski simulator either were instructed to delay the forcing of the platform until after it had passed the center of the apparatus—a performance characteristic that had been found to be associated with expert performance (e.g., Vereijken, 1991)—or were given no further instructions. Wulf and Weigelt found that the instructions did not enhance the learning of this task; rather, they were *detrimental* to performance during practice and transfer to a "stress" situation, relative to no instructions. These findings might appear surprising at first. Yet they seem to be in line with the results of subsequent studies (Shea & Wulf, 1999; Wulf, Höß, & Prinz, 1998; Wulf, Lauterbach, & Toole, 1999; Wulf, Shea, & Park, 2001), which showed that instructions that direct the performers' attention to their *body movements*—similar to the instructions given in Wulf and Weigelt's (1997) study—are not very effective.

Specifically, in these studies, Wulf and colleagues compared the effects of instructions that direct the learner's attention to the body movements that are required to produce the goal action (*internal* focus of attention) with the effects of those that direct his or her attention to the external effects that these movements have on the environment (*external* focus of attention). For example, using the ski simulator task, Wulf, Höß, and Prinz (1998, Experiment 1) instructed one group of learners to focus on their feet and to try to exert force with the right foot when the platform moved to the right (i.e., to delay the force onset of the left foot until the reversal point of the platform) and vice versa (internal focus group). Another group received basically the same instructions; the only difference was that these participants were instructed to focus on the wheels that were located directly under their feet. That is, the participants were instructed to exert force on the right pair of wheels when the platform moved to the right and vice versa (external focus group). The results indicated that the latter condition was much more effective for the production of large movement amplitudes than was the internal focus condition in both practice and retention, which was not different from a control condition without additional instructions (see Figure 4). Thus, the instructions that directed the learners' attention to the *effects* of their movement were more beneficial for learning than the instructions focusing the learners' attention on their own movements. Wulf, Höß, and Prinz replicated these findings in a second experiment. In that experiment, the learning of the stabilometer task was also enhanced by an external focus of attention (markers attached to the board in front of each foot), relative to an internal attentional focus (feet).

In a subsequent study, Wulf, Lauterbach, and Toole (1999) examined the generalizability of the learning advantages of an external focus of attention to the acquisition of sports skills. While practicing pitch shots in golf, the participants' attention was directed either to the swing of their arms (internal focus) or to the motion of the club head (external focus). Here again, the external-focus instructions greatly enhanced the accuracy of the shots in practice and in delayed retention, as compared with the internal-focus instructions. Recently, external-focus benefits have also been found for tennis (Maddox, Wulf, & Wright, 2000). The findings demonstrate that this effect seems to be generalizable to the acquisition of other real-world skills as well.

The results of a study by Riley, Stoffregen, Grocki, and Turvey (1999) are nicely in line with these findings. Riley et al. measured postural sway when participants, standing upright with their eyes closed, touched a curtain very lightly with their fingertips. (A curtain was used because it would not provide any mechanical support for posture.) Interestingly, touching the curtain significantly reduced postural fluctuation, as compared with not touching it, but only when the participants were asked to minimize movements of the curtain resulting from their touch (*touch-relevant* condition). When the participants were told that touching the curtain was irrelevant for the experiment (*touch-irrelevant* condition), postural sway was basically the same as under no-touch conditions. These findings corroborate the view that distracting performers from their own movements by having them focus on an external movement effect can greatly enhance performance.

Similar observations were made by Singer, Lidor, and Cauraugh (1993), who had participants practice a ball-throwing task with different attentional strategies. They found that a *nonawareness* strategy and the so-called *five-step approach*, in which performers were instructed to focus on a situational cue (e.g., the center of the target), resulted in more effective practice performance and (immediate) dual-task transfer than did an *awareness* strategy, in which learners were to focus on their own movements. The

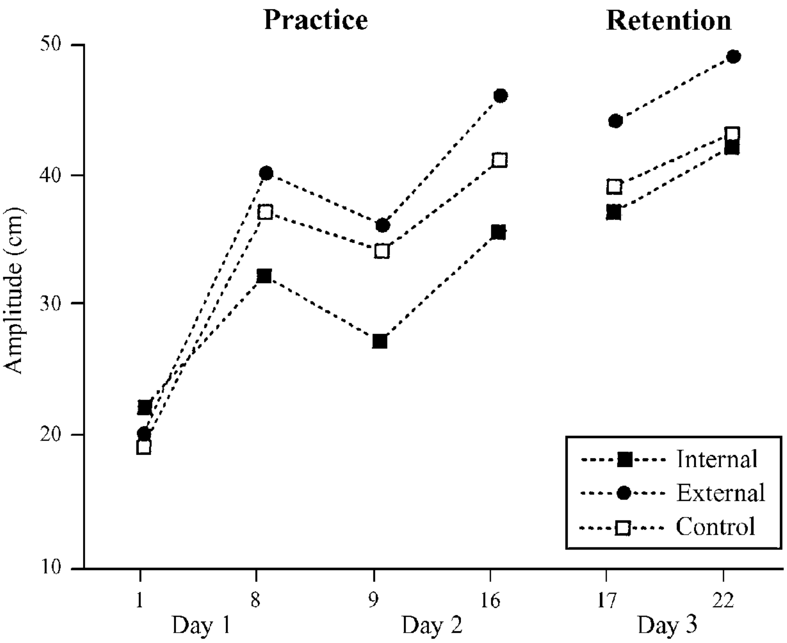


Figure 4. Average movement amplitudes of the internal-focus, external-focus, and control groups during practice (Days 1 and 2) and retention (Day 3) on the ski simulator in Experiment 1 of Wulf, Höß, and Prinz (1998). An external focus of attention enhanced the learning of large-amplitude movements, relative to an internal focus and to no instructions regarding the attentional focus.

awareness group was no more effective than a control group without strategy-related instructions. Even though the instructions to focus on a situational cue did not necessarily direct the performers' attention to the effects of their movements, these instructions might at least have served to direct their attention away from their own movements. Also, Baumeister (1984) demonstrated that self-focused attention on motor performance—for example, from competition, a cash incentive, or audience-induced pressure—can disrupt performance (see also Baumeister & Steinhilber, 1984). In addition, there is plenty of anecdotal evidence for the detrimental effects of paying attention to the coordination of one's movements, at least when it comes to the performance of well-practiced skills (e.g., Gallwey, 1982; Schmidt, 1988; Schneider & Fisk, 1983).

One question related to the use of attentional strategies is whether there might be individual differences in the preference and, perhaps, in the effectiveness of the attentional focus or whether the advantage of concentrating on the effects of one's movements, rather than on the movements themselves, is a general phenomenon. To examine this question, Wulf, Shea, and Park (2001) gave participants the option to adopt either an internal or an external focus of attention. In their study, participants learning to balance on the stabilometer were asked to find out for themselves which type of attentional focus would work better for them. In a retention test, the participants were asked to adopt either an internal or an external attentional focus, depending on which one they had found to be more advantageous during the first 2 days of practice. Of interest was, first, the number of learners who would find an internal or external focus to be more effective and, second, the performances of these subgroups (if any), especially on the retention test. The results provided further support for the advantages of an external focus of attention: A considerably greater number of participants chose to focus on the markers that were located in front of their feet (*n* = 16), rather than on the feet themselves (*n* = 4). Moreover, the participants who chose to focus on the markers were clearly more effective in retention than those who focused on their feet. Thus, these results provide support for the view that the beneficial effect of an external, relative to an internal, attentional focus is a general and robust phenomenon.

Feedback. The advantages of focusing on the outcome of one's movements, as compared with focusing on the movements themselves, not only might be relevant for the formulation of instructions, but also could have implications for the feedback that is given to the learner. C. H. Shea and Wulf (1999) therefore examined whether feedback would also be more effective if it directs the performer's attention away from his or her own movements and to the effects of these movements—that is, if it induces an external focus of attention. C. H. Shea and Wulf used the stabilometer task and presented two groups of participants with the same concurrent visual feedback, which essentially consisted of the platform movements' being displayed on a computer screen. However, whereas one group of learners was informed that the feedback represented their own movements (internal focus), the other group was told that the feedback represented lines that were marked on the platform in front of each of the performer's foot (external focus). C. H. Shea and Wulf argued that, if the learning advantages of an external focus of attention are generalizable to the feedback that is given to the learner, similar benefits should be found for the external-focus, relative to the internal-focus, feedback condition. Also, to determine whether augmented internal-focus or external-focus feedback would result in additional benefits, relative to only giving performers internal-focus and external-focus instructions (as Wulf, Höß, & Prinz, 1998, had done in their Experiment 2), two groups with either internal- or external-focus instructions were also included.

The results demonstrated that learning was more effective not only when performers were given external-focus instructions, relative to internal-focus instructions, but also when they were provided "external" relative to "internal" feedback (see Figure 5). That is, even though the feedback display was identical for the two feedback groups, the feedback group that had adopted an external focus of attention had lower errors than the feedback group with an internal attentional focus. This suggests that the feedback given to performers during practice can be more effective if it directs their attention to the movement effects, rather than to the movements themselves.

Interestingly, the feedback provided to learners in the C. H. Shea and Wulf (1999) study *generally* enhanced performers' ability to maintain their balance on the stabilometer, relative to no feedback, even though the feedback could have been argued to be redundant with respect to their intrinsic feedback (Magill, Chamberlin, & Hall, 1991). That is, the learners had visual and kinesthetic feedback available to inform them about the platform's deviation from the horizontal. Yet the visual display of the platform movements on the screen considerably benefited their performance, as compared with the no-feedback conditions. One possible reason for this added benefit of the feedback is that it might have incremented the degree to which the learners were able to maintain an external focus of attention, independent of the (internal- or external-focus) instructions given to the learners. It is also interesting to note that the withdrawal of the feedback in retention had no detrimental effect on performance. This is in contrast to other studies, where the withdrawal of concurrent feedback resulted in clear performance decrements (e.g., Schmidt & Wulf, 1997; Vander Linden et al., 1993; Winstein et al., 1996). Both the fact that the feedback provided in this experiment considerably enhanced performance during practice, even though it was redundant with respect to the performer's intrinsic feedback, and the fact that there was no performance decrement for the feedback groups when the augmented feedback was withdrawn indicate that the function of augmented feedback was not only informational or motivational in nature (see Adams, 1987). Rather, these findings seem to suggest that feedback can have the capacity to induce an external focus of attention, independent of attentional focus instructions, that benefits performance and learning.

In contrast to the experimental technique used by C. H. Shea and Wulf (1999), where the feedback given to different groups of participants was identical, in practical settings coaches or instructors typically provide the learner with verbal feedback that refers to that aspect of performance that needs the most improvement. That is, on the basis of what the coach considers to be the critical mistake or flaw, he or she gives feedback that will hopefully help the performer to make appropriate changes on subsequent attempts. The goal of a study by Wulf, McConnel, Gärtner, and Schwarz (in press) was therefore to examine the generalizability of the external-focus feedback benefits to the learning of sport skills under conditions that approximate those of athletic training situations. In their Experiment 1, different feedback statements were selected that are often used in volleyball training and that refer to the performer's body movements (internal-focus feedback). These statements were "translated" into statements that basically contained the same information but directed the learners' attention more to the movement effects. For example, instead of instructing learners to shift their weight from the back leg to the front leg while hitting the ball (internal focus), they were instructed to shift their weight toward the target (external focus). After every fifth practice trial, the performer was provided with the feedback statement that was deemed most appropriate on the basis of his or her performance on the previous trials.

The results showed that the accuracy of the serves was greatly enhanced by the external-focus, relative to the internal-focus feedback, not only during practice, but also after a 1-week retention interval in a retention test without feedback. That is, the feedback that avoided direct references to the performer's body movements led to a greater accuracy in hitting a target. This was true not only for novices, but also for advanced player who already had experience with the "tennis" serve. Furthermore, this advantage in the movement outcome was not accomplished at the expense of movement form. As was determined through expert ratings, both types of feedback led to similar improvements in form. That is, although the movement form in the novice group was degraded by internal-focus feedback during practice, this group caught up with the external-focus group in the retention test, where the feedback was withdrawn. Apparently, these participants "recovered" from the detrimental effects of the feedback that directed their attention to their movement coordination in the no-feedback retention test. For the experts, external-focus feedback tended to result in a better movement form than did internal-focus feedback during both practice and retention.

The results of recent study by Todorov, Shadmehr, and Bizzi (1997) also suggest that feedback about the movement effect appears to be more beneficial than feedback

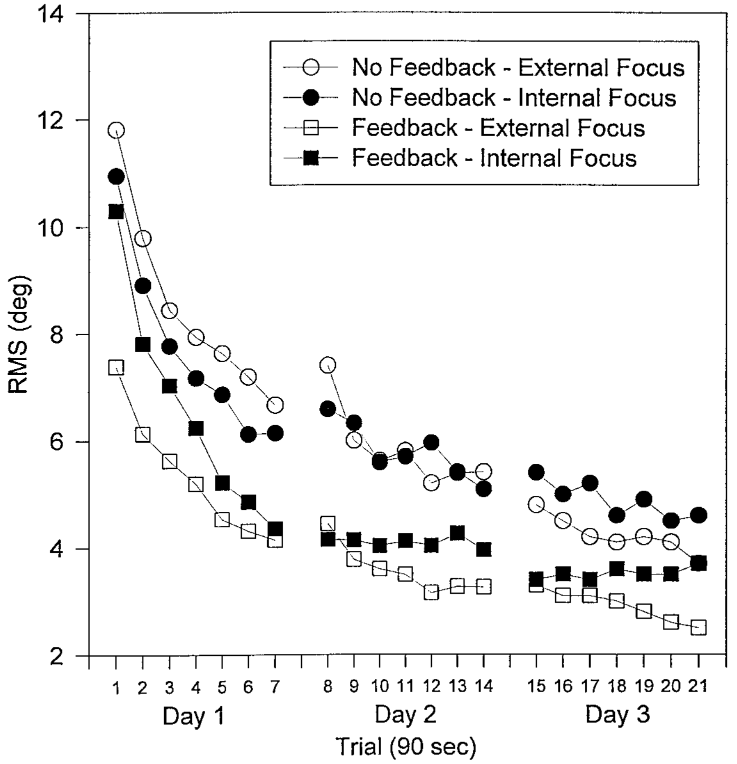


Figure 5. Root-mean square errors (RMSEs) of the no-feedback/external-focus, no-feedback/internal-focus, feedback/external-focus, and feedback/internal-focus groups during practice (Days 1 and 2) and retention (Day 3) in the C. H. Shea and Wulf (1999) study. Both feedback and an external focus of attention enhanced learning of the stabilometer task.

related to the movements that produced it. Todorov et al. argued that the highest level of motor planning and control seems to be in terms of the kinematics of the end-effector and that, therefore, the feedback given to the learner should be most effective if it represents the movements of the end-effector, rather than the body movements. Even though they did not compare these two types of feedback, Todorov et al. showed that the learning of table tennis shots was enhanced by providing performers with concurrent feedback about the trajectory of their paddle (in relation to the paddle trajectory of an expert). Those participants receiving this type of feedback were more accurate in hitting the target than were the participants who were provided verbal feedback (on gross errors) and who hit 50% more balls. It is conceivable that at least part of the reason for the effectiveness of feedback about the paddle motion was that it induced an external focus of attention, whereas the control participants (without feedback) paid more attention to their own movement pattern.

Theoretical considerations. The findings reviewed above suggest that giving learners instructions or feedback that direct their attention to the coordination of their body movements (i.e., induce an internal focus of attention), which are often used in teaching motor skills, might not be optimal for learning. Rather, they demonstrate that motor skill learning can be enhanced by focusing the learners' attention on the effects of their movements (i.e., by inducing an external attentional focus).

The exact reasons for the beneficial effects of an external, relative to an internal, focus of attention are still relatively unclear. However, more than 100 years ago, William James (1890) already had suggested that actions are controlled more effectively if attention is directed to the (intended) outcome of the action, or its "remote effects," rather than to the "close effects" that are directly associated with it, such as the kinesthetic feedback. Similar ideas have been proposed by Lotze (1852). According to Lotze, movements are represented by codes of their perceived effects, and the desired outcome has the power to guide the action so that this outcome is achieved. More recently, Prinz and colleagues (Prinz, 1992, 1997; Prinz, Aschersleben, Hommel, & Vogt, 1995) and Hommel (1997) have taken up James's and Lotze's ideas that actions are planned and controlled by their intended effects (*action effect hypothesis*; Prinz, 1997). In his *common coding* theory, Prinz (1990, 1997) provides a possible explanation for the advantages of focusing on the effects of one's movements, rather than on the movements themselves. Contrary to traditional views, which assume that there are different and incommensurate coding systems for afferent and efferent information (e.g., Massaro, 1990; Sanders, 1980; Welford, 1968), Prinz argued that there is a common representational medium for perception and action. According to this view, efferent and afferent codes can be generated and maintained in a commensurate way only at a distant level of representation. That is, action planning and perception typically involves *distal events*, since this is the only format that allows for commensurate coding and thus for efficient planning of action (see Prinz, 1992). Therefore, actions should be more effective if they are planned in terms of their intended outcome, rather than in terms of the specific movement patterns.

Some support for this notion comes from the findings of Proctor and Dutta (1993). In their study, participants were provided with extensive practice on a two-choice reaction task. The relations between stimulus locations, response key location, and effectors (right vs. left finger) were different for different groups of participants. In transfer, the participants were switched to new conditions, in which the spatial mapping between stimulus location and response keys, as well as the hand placement (uncrossed vs. crossed), was either the same as or different from that in practice. The important finding in the present context was that switching hand placements did not lead to increases in RT when the spatial stimulus–response mappings remained constant. However, switching hand placements did cause performance decrements when the stimulus–response mapping changed, even if the mappings of stimuli to fingers remained the same.

The idea that people "naturally" tend to focus on the effects of their actions, instead of focusing on the movements that are involved in the action, has also been put forward by Vallacher and Wegner (1985, 1987). In their action identification theory, Vallacher and Wegner proposed a hierarchical order of action identities that are used in the control of action. They argued that if lower and higher levels of action identity are available, higher level identities become prepotent. Lower levels in an action's identity structure refer to the details of the action, such as the specific movements (e.g., striking the correct keys on a piano), whereas higher levels are more related to the effects of the action (e.g., playing the melody). If the performer selects too low a level of action control—for example, because of pressure to perform well—performance is often disrupted.

It is possible that attempts to consciously control movements interferes with automatic motor control processes, whereas focusing on the movement effects allows the motor system to more naturally self-organize (e.g., Kelso, 1995), unconstrained by conscious control. Focusing on the remote effects of the movement might serve to let unconscious control processes take over, "freeing up" conscious aspects of attention to be directed to other aspects of the task, resulting in more effective performance and learning. This might be particularly advantageous for complex skills, where consciously trying to control the many degrees of freedom is almost bound to result in failure, particularly early in practice (see Willingham, 1998, for a different perspective).

Support for this assumption has recently been found in studies by McNevin, Shea, and Wulf (in press) and Wulf, Shea, and Park (2001). In these studies, the frequency characteristics (fast Fourier transformation, FFT) of the balance records of participants balancing on the stabilometer were determined. Participants who focused on their feet (internal focus) showed higher amplitude and lower frequency movement adjustments than did participants focusing on markers in front of their feet (external focus; Wulf, Shea, & Park, 2001). Furthermore, in the McNevin et al. study, two groups that focused on markers at a greater distance from the feet made even more and smaller corrections in maintaining their balance than did a group that focused on the markers close to the feet. High-frequency responding has been argued to be a characteristic of a biological system with more active degrees of freedom, whereas constrained or compromised perceptual–motor systems exhibit lower frequency components (see Newell & Slifkin, 1996, for a discussion of this issue). McNevin et al. proposed a *constrained action hypothesis* to account for the external focus benefits. According to this hypothesis, performers focusing on their body movement, or on an effect that occurs in close proximity to their body, tend to actively intervene in the control of their movements. Thus, one advantage of focusing attention on a (distant) movement effect seems to be that it allows unconscious processes to control the movements required to achieve this effect, resulting in fast movement adjustments and generally enhanced performance and learning.

In summary, it is important to note that, to date, research on focus of attention has been directed only to relatively complex skills. Presumably, complex skills have been used for these experiments because it was felt that an internal focus of attention might be detrimental to learning, because it increases the already high cognitive loads associated with the task. Alternatively, an external focus might actually reduce cognitive load by taking advantage of self-organizing capabilities of the motor system. Recent results by Wulf, McNevin, and Shea (2001) support this view. In their study, participants balanced on the stabilometer, and probe RTs were taken as a measure of the attention demands required under external versus internal attentional focus conditions. External-focus participants demonstrated lower probe RTs than did internal-focus participants, indicating reduced attention demands associated with an external focus. Thus, these results are in line with the view that complex skill learning can be enhanced by reducing the attentional and/or motor control demands associated with it.

Observational Learning

Another factor that might be more effective for the learning of complex skills, relative to more simple skills, is observational learning. The study of observational learning has been the focus of considerable research since the early 1960s. In fact, observational learning is one area of motor behavior research that has typically utilized tasks that are relatively complex, although there are a number of examples of simple tasks being used as well.

For the most part, observational learning, although generally considered not as effective as physical practice, has been demonstrated to be a viable method of practicing complex motor skills (e.g., Bachman, 1961; Landers & Landers, 1973; Martens, Burwitz, & Zuckerman, 1976; Schönfelder-Zohdi, 1992; C. H. Shea, Wulf, & Whitacre, 1999; Sidaway & Hand, 1993; Whiting, 1988; see McCullach et al., 1989, for a review). On the other hand, observational practice in learning simple tasks has led to equivocal findings. In a number of experiments involving simple motor tasks (e.g., Blandin, Proteau, & Alain, 1994; Burwitz, 1975; Lee & White, 1990), observation has been shown to enhance learning. However, other experiments have shown little or no benefit of observation (e.g., Brown & Messersmith, 1948; Burwitz, 1975; Wright, Li, & Coady, 1994).

There are at least three possible reasons for why observational practice seems to be more effective for complex skills than for simple skills. First, there may be fundamentally more to "see" and, therefore, more to be extracted as the result of observation of relatively complex tasks, as compared with simple tasks. This issue is illustrated by Burwitz (1975), who found observation beneficial when he used a Bachman ladder task, a relatively complex task, in one experiment and no differences when a pursuit rotor task, a simple task, was used in another experiment. He noted that the participants reported in postexperiment interviews that they had found the movement pattern leading to success in the task "visible" only in the Bachman ladder task. This led Burwitz to conclude that the benefits of observation were mediated by task difficulty. In a similar vein, Gould (1980) suggested that observation was more effective when the informational load of the task was high, which is often the case for complex tasks, than when it was low, which is more typical of simple tasks. These findings, along with psychophysical evidence on the perception of biological motion (e.g., Johansson, 1973), where observers were effective in reducing complex arrays into relatively simple patterns of relative motion, prompted Scully and Newell (1985) to propose that observers are effective in reducing perceptual complexity by extracting patterns of coordination (relative motion), rather than information that leads to the specific scaling of the action pattern. These theorists have argued that because observers do not actually execute the movement and do not process direct sensory information, observers are not as effective as the model, who is physically practicing a skill, in learning to scale the movement sequence. However, observers appear to be able to extract information necessary to construct appropriate coordination patterns (Schönfelder-Zohdi, 1992; Scully & Newell, 1985; Whiting, 1988) and determine appropriate implementation strategies (Kohl & Shea, 1992). In addition, observation may provide the learner with a better "picture" of how the various subcomponents of a complex task fit together to form the whole task. Just as analogies have been shown to reduce memory demands by providing a framework in which to organize memory (e.g., Anderson & Fincham, 1994; Fery & VomHofe, 2000; Zamani & Richard, 2000), observation may facilitate the structuring of the memories supporting the movements, thus effectively reducing the total memory demands. When the task demands are relatively simple, this may not be important, but when the demands are high and subcomponents must be properly integrated, the influence could be much larger. Thus, even though observational practice might not be as effective as physical practice in training specific task characteristics, because some types of important processing are unique to physical practice and cannot be developed effectively during observation, observational practice is viewed as a viable training method for teaching general characteristics of complex tasks.

Second, it is possible that observational practice offers the observer the opportunity to engage in processing that would not or could not be effectively carried out early in practice—particularly when learning a complex skill—when most, if not all, of the cognitive resources of the performer are required to physically perform the new task (Kohl & Fisicaro, 1996; C. H. Shea, Wright, Wulf, & Whitacre, 2000). That is, the observer may be able to extract important information from observation concerning appropriate coordination patterns or subtle requirements of the task and/or evaluate effective or ineffective strategies that would be difficult, if not impossible, to do while attempting a new task, because of the high demands on cognitive resource. From this perspective, observational practice offers processing opportunities in complex tasks that would not generally be afforded under physical practice conditions until the skill had become well learned (automated) and attention demands had been greatly reduced. However, later in practice, inappropriate or even incorrect performance elements may have become well learned and therefore more dominant and difficult to change (see Wightman & Lintern, 1985). Thus, since complex skills are generally more attention demanding, the beneficial effects of observational practice should be seen more clearly for complex tasks. Simple tasks, on the other hand, for which cognitive demands tend to be much lower, may not benefit as much from the reduced processing loads characteristic of observational practice.

If physical and observational practice offer unique opportunities for processing that may independently increment learning, acquisition protocols that combine physical and observational practice should be effective training procedures. Some support for this notion was found in experiments by Shebilske and colleagues (e.g., Shebilske, Regian, Arthur, & Jordan, 1992) and C. H. Shea, Wright, Wulf, and Whitacre (2000). Shebilske et al., for example, used a special form of dyadic training, the so-called *active interlocked modeling* (AIM) protocol. Their participants practiced a video game ("Space Fortress"), where one partner controlled half of the complex task (e.g., the keyboard), whereas the other partner controlled the other half (e.g., the joystick). While controlling either the keyboard or the joystick, the participants were able to observe the other member of the dyad perform his or her respective task. Presumably, this was possible because the attentional and cognitive demands required to control half of the total task were reduced to the extent that they could allocate resources to observation. Hands-on practice of one half and observational practice of the other half of the control procedures were switched from trial to trial. Thus, as compared with an individual training group that controlled the whole task on all the practice trials, for the participants in the AIM dyad, the informational load was reduced. On test games that required control of the whole task, however, there were no differences between groups—that is, both groups showed the same amount of learning (also see Jordan, 1997, for a meta-analysis). Thus, facilitating practice by reducing the task demands had no detrimental effect on learning, as compared with practicing the whole task.

Many tasks do not lend themselves to dual control (i.e., segmentation) as does "Space Fortress," however. Another potentially efficient and effective training protocol, which involves observation and can be easily applied to many training environments and tasks, can be constructed by having participants alternate between physical and observational practice. Such a protocol takes advantage of the intervals between trials/sessions: While one learner is engaged in physical practice, the other is afforded the opportunity to observe. The participants change roles on subsequent trials. Using such a protocol, C. H. Shea et al. (2000) even found learning advantages of combined observational and physical practice over physical practice alone. C. H. Shea et al. (2000) had participants learn to alternately press two response keys with the first finger of their right and left hands in an attempt to keep a "dot" centered on a target line (similar to the Pew, 1966, task). The "dot" accelerated to the left when the right key was depressed and to the right when the left key was depressed. A unique feature of these experiments was the inclusion of a transfer test. The authors argued that the transfer test emphasized the relative characteristics of the coordination pattern and appropriate movement strategies but deemphasized the specific characteristics of the acquisition task. Thus, if observers are effective in extracting from observation the relative characteristics of the task (e.g., Scully & Newell, 1985) and determining effective strategies (Kohl & Shea, 1992), as has been proposed, the transfer task should be sensitive to these aspects of the task. In contrast, performance on a retention test, which has been utilized almost exclusively in studies of observation, could be dominated by specific, rather than general, characteristics of the task.

When 50% of the physical practice trials were replaced with observational practice, no decrements in retention performance were noted, as compared with a group that practiced physically on all practice trials (C. H. Shea et al., 2000, Experiment 2; also see Weeks & Anderson, 2000). More important, the performance of the combined observational and physical practice group was superior to that of the physical practice group on the transfer test. Thus, even though the participants in the combined group performed only half the physical practice trials the physical practice participants did, they performed equally well on the retention test and more effectively than the physical practice group on the transfer test. These findings demonstrate that alternating observational practice with physical practice trials can be quite effective, presumably because the interspersed observational trials give learners the opportunity to perform information-processing activities that they would not be able to do while performing a complex, highly attention-demanding skill.

A third reason why observational practice might be particularly useful for complex skill learning refers to training efficiency. Owing to the relatively high physical demands, practicing complex motor tasks often requires the insertion of rest periods between trials. Providing learners with observational practice during rest intervals—for example, by having them watch a partner perform—would enhance training efficiency, since two (or more) learners could be trained in the same amount of time as one. Learning efficiency is assessed when one considers the time, money, potential for injury, energy, and/or other personal and experimental resources that are expended in order to conduct the training sessions. Clearly, from a personal standpoint, observational practice requires the expenditure of less physical energy, reduces the risk of injury, and is not dependent on equipment or specific space requirements, as in the case of physical practice. The issue of learning efficiency, although relevant to the study of both simple and complex skill learning, is especially important for complex skills, because these skills generally take longer to learn, often are more physically demanding, in many cases introduce the potential for more risk, and generally require more specialized equipment or facilities than do simple skills.

In the experiments by Shebilske et al. (1992) and C. H. Shea et al. (2000), doubling the number of participants trained without an increase in time and other resources led to increases in training efficiency of at least 100%, while not sacrificing, and even enhancing, learning effectiveness. C. H. Shea et al. (1999) examined the effectiveness of this type of combined physical and observational practice protocol for the learning of a dynamic balance task (stabilometer), which, like many other complex, continuous motor tasks, requires intervals between practice trials to avoid fatigue and provide relief from the high attention/concentration demands. C. H. Shea et al. (1999) utilized a combined practice protocol that had participants work in dyads so that they alternated between physical and observational practice. They also allowed the participants to engage in undirected dialogue during the rest interval between practice trials. The effectiveness of this training protocol was compared with that of individual training with the same number of physical practice trials.

The results showed that practice with a partner was more effective than individual practice. Even though there was an initial performance decrement under dyad practice

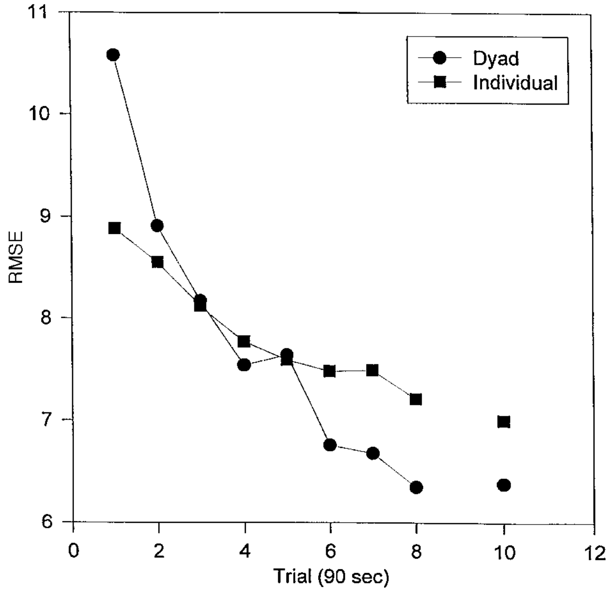


Figure 6. Root-mean square errors (RMSEs) of the individual and dyad groups during acquisition and retention in the C. H. Shea, Wulf, and Whitacre (1999) study. Individual practice consisted of physical practice with rest periods, whereas dyad practice involved alternating physical practice, observation, and discussion. Dyad practice produced more effective learning than did individual practice.

conditions in acquisition, relative to individual practice, the dyad group participants quickly caught up with the individual group participants and even tended to be more effective at the end of the acquisition phase (see Figure 6). More important, learners who had practiced with a partner showed more effective delayed retention performance than did individual learners. This is particularly remarkable since retention trials were performed under individual-performance conditions. That is, the benefits of dyad training transferred to a situation in which participants had to perform individually.

In summary, it appears that observational practice is more uniformly effective in complex than in simple tasks, in which there is more for the observer to "see" and, therefore, extract from observation (e.g., Burwitz, 1975; Gould, 1980). In addition and perhaps most important, observational practice offers a form of practice in which the cognitive demands are sufficiently reduced, because the observer is not required to physically perform the task and can concentrate on the fundamental elements of the task and the relationships between components and can devise or evaluate strategies that result in effective task performance. The latter types of processing afforded under observation practice should be especially helpful when observation and physical practice are combined. It is also important to note that combined observation and physical practice protocols have the potential to greatly increase learning efficiency without sacrificing learning effectiveness (C. H. Shea et al., 2000; C. H. Shea et al., 1999). This latter consideration is especially important for complex skills that often require that more time and other resources be devoted to training than for simple skills that can be effectively learned with relatively little practice.

SUMMARY, FUTURE DIRECTIONS, AND CONCLUSIONS

For a long time, the use of relatively simple tasks has been predominant in motor-learning research. In statements that may have had a profound influence on many researchers in the motor domain, Adams (1971) addressed this issue by stating that

> the villain that has robbed "skill" of its precision is applied research that investigates an activity to solve a particular problem, like kicking a football, flying an airplane, or operating a lathe. . . . This approach is backwards for scientific productivity because it results in disconnected pockets of data that lack the unifying ideas that are general scientific principles. The task-centered approach is justified when practical reasons require us to know about task and efficiency in them, but it is a limited way of achieving the larger scientific goals of laws and theory. (pp. 112–113)

These statements by Adams were clearly aimed at the differences between applied and theoretical research. However, researchers may interpret this as an indictment of complex skills by association. In contrast, Hoffman (1990) and Locke (1990) have argued that researchers have "preferred to look for answers in the brightness of the laboratory, even though the most valuable findings may lie in the darkness of real-world settings" (Hoffman, 1990, p. 150). In essence, Hoffman and Locke argued that the study of simple skills in sterile laboratory settings has not been successful in determining underlying processes and principles or in providing meaningful information to practitioners. To some degree, we agree with their statements, because there has been a rather strong tendency not to explore the boundary conditions of learning effects, particularly in terms of the complexity of the task and the level of skill of the learners.

Presumably, simple skills are used so extensively in motor learning and control because researchers and theorists believe that by reducing a task down to its fundamental elements, the processes (or mechanism) can be exposed more completely and manipulated more effectively to answer theoretical questions. These notions appear to have been borrowed in motor learning and control, as well as in other fields of study in the social sciences, from the biological and physical sciences. For example, in exercise physiology today it is *en vogue* to study movement production systems not only at the mechanism level, but also at the molecular level. Although the reductionist approach has been productive (although this has been debated) in other disciplines, this pivotal question should be questioned more openly by motor-learning and control researchers (see Locke, 1990). The most obvious reason for utilizing simple skills, although not the most lofty, involves the efficiency with which experiments can be conducted. In many motor-learning and control experiments, including many of our own, the tasks were (1) easily and inexpensively constructed, (2) novel to participants (so that previous practice would not confound the results), and (3) characterized by a single performance measure, and, of course, (4) practice could be completed (often to apparent performance asymptote) in a single session. In numerous experiments, as few as 54 trials were utilized, perhaps involving as little as 15 min to learn the task. Clearly, being able to complete experiments in 1 or 2 days is efficient, provided efficiency has not been traded off in terms of the power of the experiment to tell us something about skill learning in general. Thus, we agree with our pedagogy colleagues, Hoffman (1990) and Locke, that the study of simple tasks has not been effective in determining meaningful principles that have application to more complex skills.

The importance of using ecologically valid tasks, rather than artificial laboratory tasks, has also been discussed extensively in the area of memory research (e.g., Neisser & Winograd, 1988). Whereas some argue that the principles derived from laboratory research do not apply to the way memory functions in real-world situations (e.g., Neisser, 1991), others point out the value of basic research conducted in controlled laboratory settings for theory development and its high generalizability to everyday problems (e.g., Banaji & Crowder, 1989). This debate has been concerned mainly with the ecological validity of the research methods used. Although we see a need to use more complex skills in motor learning research, we do not advocate the use of more naturalistic methods and settings (Neisser, 1991). In fact, we agree with Banaji and Crowder that "the more complex a phenomenon, the greater the need to study it under controlled conditions, and the less it ought to be studied in its natural complexity" (p. 1192). We would also like to point out that we do not want to discredit the value of fundamental research using simple skills for discovering principles of learning. This type of research has contributed immensely to our understanding of the learning process. Furthermore, the validity of this research does not depend on the immediate applicability of the identified principles to real-world problems. We do believe, however, that the inclusion of more complex and ecologically valid tasks in our research would further enhance our understanding of learning.

A Case Against the Utilization of Primarily Simple Tasks in the Study of Motor Skills

As we have shown in the first section of this review, principles developed on the basis of simple skills are not always generalizable to more complex skills. Some factors that enhance the learning of simple skills do not appear to be beneficial for complex skill learning. For example, frequent feedback has been found to degrade the learning of simple skills. Yet frequent feedback can be advantageous, if new complex skills have to be learned (e.g., Guadagnoli et al., 1996; Wulf, Shea, & Matschiner, 1998). Similarly, blocked feedback, although detrimental for simple skill learning, relative to random feedback, seems to be beneficial for the learning of complex skills (e.g., Lee & Carnahan, 1990; Wulf, Hörger, & Shea, 1999). Furthermore, random practice, which has often been shown to enhance motor learning when simple tasks were used, does not seem to be beneficial for the learning of more complex tasks (or for inexperienced learners); rather, blocked practice can result in more effective learning in these cases (e.g., Albaret & Thon, 1999; Hebert et al., 1996; J. B. Shea & Morgan, 1979). Finally, frequent physical assistance can enhance the learning of complex motor skills, at least if it facilitates the exploration of movement strategies or techniques, relative to practice without the help of physical guidance (Wulf, Shea, & Whitacre, 1998). The obvious lack of generalizability from simple to complex tasks suggests that the utilization of complex tasks is essential in order to gain a more complete understanding of the processes underlying motor skill learning and in order to be able to give valid recommendations for practical settings. Thus, our recommendation is not to eliminate research conducted with simple tasks but to more broadly include tasks at the other end of the difficulty spectrum. Only by including tasks of varying difficulty can the parametrics of motor-learning principles be discerned.

Moreover, as was shown in the second section of our review, some practice variables might be particularly effective for the learning of complex skills, relative to more simple skills. That is, the importance of such variables as observation of or interaction with a partner (e.g., C. H. Shea et al., 1999) or the attentional focus induced by the instructions or feedback provided to the learner (e.g., C. H. Shea & Wulf, 1999; Wulf, Höβ, & Prinz, 1998) might not be apparent when studying skills with few degrees of freedom, where the information-processing demands are comparatively low. Thus, the relevance of such variables for motor learning might not be discovered by using simple tasks.

These findings call into question the adequacy of utilizing primarily simple tasks in the study of motor learning and control (see Hoffman, 1990, for an earlier discussion on this topic). The usefulness of simple laboratory tasks for understanding the processes underlying motor learning seems to be limited, and making generalizations to the training of complex skills on the basis of such findings appears to be problematic. As we have shown, some of the theoretical concepts developed from the research on simple skills are not applicable to complex skills. It seems that with motor skill learning, positive and negative effects of practice variables change, depending on the complexity of the task and the demands the task places on the learner. Therefore, more research is needed that contrasts simple and complex skills and also takes into account the skill of the performer. Until these boundary conditions are determined, valid principles and, thus, comprehensive theories cannot be developed.

Therefore, future research in motor learning should include, more than is common at present, skills that require the control of several degrees of freedom, load or overload the perceptual, cognitive, and/or attention systems, have multiple emphases that need to be integrated, and/or perhaps even involve whole-body movements or real-world skills. This not only may provide a more reliable basis for giving recommendations for the teaching of motor skills in applied settings and bring to the forefront new lines of research (e.g., practice efficiency, attentional focus) and principles that are not typically at issue with simple skills, but also should further our understanding of and our insights into motor learning and control processes in general.

Do Complex Skills Late in Practice Operate Similarly to Simple Skills Early in Practice?

As we have shown, several variables that are detrimental to simple skill learning actually benefit the learning of complex skills. For example, frequent feedback has been found to enhance the learning of the ski simulator task (Wulf, Shea, & Matschiner, 1998), as well as a complex two-hand coordination task (Swinnen et al., 1997). An important question regarding the frequency of feedback is whether the learning of complex skills can also be enhanced by reducing feedback later in practice. It is possible that with considerably more practice (than the 2 days used in the Wulf, Shea, & Matschiner, 1998, study), the learning of a complex task like this is also affected negatively if feedback is provided too often. Whether the acquisition of complex skills eventually follows the same principles as the learning of simple tasks or whether the danger of learning's being degraded by too much feedback is generally reduced or nonexistent for complex motor skills needs to be determined in future studies.

Similarly, even though blocked feedback was beneficial for the learning of the ski simulator task when provided on 4 days of practice (Wulf, Hörger, & Shea, 1999), it is conceivable that more frequent changes in the task component that feedback is provided about would eventually also be advantageous for complex skills, as has been shown for comparatively simple tasks (Lee & Carnahan, 1990; Swanson & Lee, 1992). With increasing amounts of practice, performance becomes less attention demanding (e.g., Fitts & Posner, 1967; Shiffrin & Schneider, 1977; Weiss, 1939), providing the learner with more capacity to handle the diversity of feedback information, which might eventually result in learning benefits. Also, in analogy to fading procedures in feedback frequency manipulations, it might be predicted that a gradual shift from blocked to random feedback schedules, with the time frame of this shift depending on the complexity of the task, would optimize skill learning. Further research is also needed to examine the effectiveness of various combinations of feedback frequency and scheduling (blocked vs. random) manipulations, as well as effects of summary or average feedback on complex skill learning at various stages of practice.

Similarly, some of the inconsistencies that have been noted in this review for CI manipulations in complex skills might be resolved if additional practice were to be provided. It is possible that with *relatively* little practice (the exact amount may increase with increasing task difficulty), blocked practice groups may outperform random-practice groups (see C. H. Shea et al., 1990). With additional practice, the differences may diminish, with random practice eventually resulting in superior retention or transfer performance. The absolute amount of practice that may be required for a particular effect to emerge may be quite small for very simple tasks and quite extensive for more complex tasks.

Although some experiments have investigated how the relative difficulty of a task changes as a result of practice experience by either looking at the performance of learners after little or more extensive practice (e.g., C. H. Shea et al., 1990) or contrasting inexperienced and experienced performers on a single task (e.g., Del Rey et al., 1982; Guadagnoli et al., 1996), little, if any, research has looked at this question systematically. One experimental approach might be to utilize a relatively complex skill that can be broken down into its fundamental components. The important question then would be the following: Do the ways in which the components have been learned really provide insight into how the whole task is learned? To some extent, experiments looking at part practice in complex skills have addressed this issue from the other side: Does practicing a simplified, fractionated, or subcomponent version of a more complex skill enhance the learning of the complex (whole) skill? What we are suggesting is a closer look at the learning of the components, looking at the extent to which analyses of the learning of these task components provide insight into the learning of the whole task.

Another, more longitudinal approach would be to determine the influence of various practice manipulations early and late in practice, in an attempt to determine which practice manipulations enhance learning and when, in practice, the manipulation is most robust. Lai et al. (2000), for example, have demonstrated that blocked practice early in practice facilitates the learning of the relative timing pattern, whereas random practice later in practice leads to enhanced absolute timing performance. Reversing the practice schedule (random practice early and then blocked practice later) resulted in poor relative and absolute timing performance. The important point is that factors that exert influence in a learning situation may do so differentially across practice and task difficulty.

The differential effectiveness of various practice variables (depending on the task and experience of the learner) suggests that judging difficulty on the basis of external characteristics may not be as productive as characterizing task situations in terms of their demands (cognitive, attentional, motor). Under a scheme based on the demands the task places on the cognitive motor system, difficulty would be considered a relative task characteristic that depends on the degree to which resources are loaded or overloaded. This perspective is consistent with the notion that motor skills with low demands benefit from practice conditions that increase the load and challenge the performer (e.g., Bjork, 1994; Lee et al., 1994; Schmidt & Bjork, 1992);

however, the acquisition of skills that place extremely high loads on the performer should benefit from conditions that reduce the load to more manageable levels (physical assistance, increased feedback, observation practice, external focus of attention).

Balancing Learning Effectiveness and Learning Efficiency in Complex Skills

Learning efficiency is a potentially important issue in the study of complex motor skills, which is clearly of less interest in the study of simple skills. Especially interesting is the degree to which learning effectiveness and learning efficiency trade off under various experimental conditions. Because of the potentially higher costs of complex skill training, in general, this is a critical question for applied reasons, but learning efficiency is also intriguing for theoretical reasons. Asking the questions “what factors allow a complex skill to be learned to a specified level of performance in less time? . . . with less effort? or . . . at less cost?” is potentially as interesting as asking the more general question “what factors influence the learning of motor skills?” Yet the question of learning efficiency and its relationship to learning effectiveness has been largely ignored in motor behavior literature.

One way to enhance training efficiency is to provide learners the opportunity to observe other learners performing. C. H. Shea et al. (2000; C. H. Shea et al., 1999) recently demonstrated quite large increases in learning efficiency for dyad training by allowing participants to alternate between physical and observational practice. This manipulation also resulted in substantial increases in learning effectiveness. Practice methods developed in future research should be evaluated in terms of both learning effectiveness and learning efficiency.

Conclusions

As we have shown in the first section of this review, principles developed through the study of contextual interference, the manipulation of feedback, and physical guidance when simple skills are utilized are not generalizable to more complex skills. In fact, research on more complex skills shows that the manipulation of practice variables that result in enhanced learning of simple skills are actually detrimental to the learning of complex skills. In the second section, we reviewed two important practice variables that have been studied primarily with complex skills and that may not be applicable to simple skills. These findings call into question the adequacy of utilizing primarily simple tasks in the study of motor learning and control. We conclude that more intensive research on complex skills is required to fully determine the generalizability of current findings, to advance motor learning and control theory to include task difficulty as a mediating factor in practice protocols, and to provide salient advice to practitioners. Furthermore, we question the relevance of research on simple skills to purposes other than understanding the control and learning of simple skills, such as deriving general motor learning principles. We propose that only when motor skills of varying complexity are included in the literature can fundamental theoretical principles be derived.

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