Schema Theory: A Critical Appraisal and Reevaluation

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ABSTRACT. The authors critically review a number of the constructs and associated predictions proposed in schema theory (R. A. Schmidt, 1975). The authors propose that new control and learning theories should include a reformulated (a) notion of a generalized motor program that is not based on motor program but still accounts for the strong tendency for responses to maintain their relative characteristics; (b) mechanism or processes whereby an abstract movement structure based on proportional principles (e.g., relative timing, relative force) is developed through practice; and (c) explanation for parameter learning that accounts for the benefits of parameter variability but also considers how variability is scheduled. Furthermore, they also propose that new theories of motor learning must be able to account for the consistent findings spawned as a result of the schema theory proposal and must not be simply discounted because of some disfavor with the motor program notion, in general, or schema theory, more specifically.

Key words: motor learning, motor program, parameter learning, relative timing, schema theory

In 1975, Richard A. Schmidt published in *Psychological Review* what was to become a seminal article in the motor behavior literature: "A Schema Theory of Discrete Motor Skill Learning." The obvious initial impact was the advent of a theoretical position that challenged Adams's (1971) closed-loop theory, which had been published just a few years earlier. Much like Adams's theory, schema theory provided the basis for a flurry of experimental work. In that work, Schmidt evaluated the theoretical constructs central to the theory and tested the predictions explicitly and implicitly proposed in the theory. The article achieved "citation classic" designation by the Institute for Scientific Information (ISI) in 1994 after amassing more than 400 citations.[1] As indicated by the still increasing number of citations (see Figure 1), the impact of schema theory appears to remain robust beyond the 25th anniversary of its publication in the year 2000. As of the end of 2004, his article has accounted for 782 citations, with 58 of those citations in the last 2 years. Even more remarkable is the broad range of journals and disciplines in which the article has been cited. Although schema theory was initially aimed at researchers in traditional motor behavior, a substantial number of the citations over the years have come from the fields of cognitive psychology, neuroscience, human factors, motor development, physical therapy, and occupational therapy. In the last 2 years, it has been cited in articles on music perception, management science, adapted physical education, speech research, teaching surgery, a number of areas in gerontology, as well as in the traditional areas of motor learning, control, and development.

Since its publication, schema theory has weathered many theoretical storms and has also prompted the development of other theoretical perspectives. For example, Gentner (1987) raised serious questions regarding the nature of timing invariance in motor skills that supposedly categorize particular classes of movements. Similarly, researchers adopting the dynamical systems perspective have provided alternative accounts of phenomena that they had previously, partially by default, explained by using motor program explanations (e.g., Kelso, 1997). At this time, however, the vast majority of motor control and learning researchers do not appear to use schema theory as a theoretical basis for conducting much of their research. Yet, recent work in which acquisition, retention, and transfer performance of motor skills has been partitioned into generalized motor program (GMP) and parameter components (e.g., Lai & Shea, 1998, 1999; Sekiya, Magill, & Anderson, 1996; Sekiya, Magill, Sidaway, & Anderson, 1994; Wulf, 1992;

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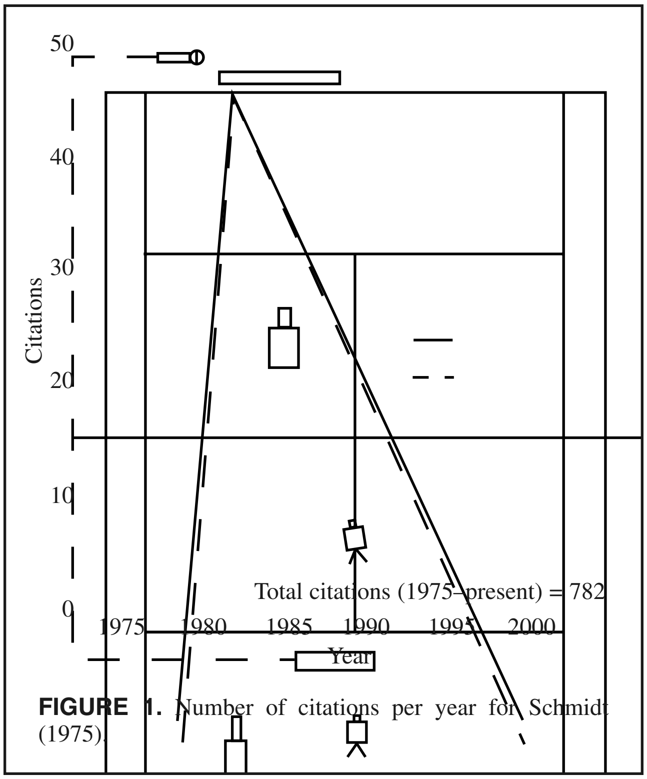

FIGURE 1. Number of citations per year for Schmidt (1975).

Wulf, Schmidt, & Deubel, 1993) has demonstrated that the direct influence of the theory is not totally void. Indeed, that research has played an important role in reshaping both the knowledge of results (e.g., Wulf & Shea, 2004) and the contextual interference (e.g., Lee & Simon, 2004; Magill & Hall, 1990) literatures. Nevertheless, for many researchers, schema theory appears to no longer offer an acceptable theoretical position but has in many ways provoked the development of alternative views and served as a model from which new theoretical positions can emerge. The bottom line is that the indirect impact of schema theory has been and continues to be widespread, as indicated by the citation record just provided.

Recently, researchers have debated the viability of schema theory assumptions in the light of newer findings from information-processing and dynamical systems theory perspectives (e.g., Newell, 2003; Schmidt, 2003; Sherwood & Lee, 2003). Not surprisingly, the conclusions differ dramatically depending on the theoretical view, with information-processing proponents (e.g., Schmidt; Sherwood & Lee) seeing more supportive evidence for schema theory predictions than do dynamical systems proponents (e.g., Newell). Our purpose in the present article is to provide—from an information-processing perspective—a critical review of recent findings regarding some of the major predictions of schema theory. Specifically, those include (a) factors that facilitate GMP and parameter learning, (b) the independence of GMP and parameter specifications, and (c) the independence of GMP and effectors used to execute a movement. We will show that although there is some support for the basic premises of schema theory (primarily when it comes to relatively simple skills learning), its assumptions are too simplistic to enable one to account for more complex learning situations. In addition, we discuss newer findings that suggest a way in which GMPs are initially developed. Those findings are important, because Richard Schmidt in proposing schema theory simply assumed the existence of GMPs and did not offer a mechanism or process whereby they were developed. Over the years, that omission has been viewed as a major limitation of schema theory.

We begin by briefly reviewing some of the basic tenets of schema theory as well as its major predictions. In the review, we focus on those predictions most directly related to the recall schema, GMP, and associated parameters. We devote the main body of the article to the review of recent findings regarding those predictions. We end with an assessment of the viability of schema theory on the basis of the current state of knowledge and offer some considerations for new theories of motor learning and control.

The Theory: Overview and Major Predictions

A major contribution of Schmidt's (1975) schema theory is that, in contrast to Adams's (1971) closed-loop theory, it provided an explanation for the control and learning of both rapid and slow movements. In addition, it provided a more economical account—from a processing and memory standpoint—of how the numerous movement variations that humans are capable of performing are produced and stored than Adams's theory did. The memory representations underlying that capability are the GMP and motor schemata (recall and recognition[2]). The GMP was proposed as a structure that is the basis for generating responses within a movement class (e.g., one's signature) that shares some invariant features such as the sequencing of submovements, relative timing, and relative forces. However, actions governed by a GMP could be scaled across one or more superficial dimensions (e.g., speed of writing movements, size of writing, and the specific muscles used) by the assignment of movement parameters, such as absolute time and absolute force, via the recall schema. Thus, when movements governed by a GMP are scaled in that way, the sequencing, relative timing, and relative force are assumed to remain essentially invariant, as if the movement could be systematically compressed or expanded in both amplitude and time (see Schmidt, 1985, 1988, for reviews). Although that view has been criticized on the grounds that exact proportional scaling is seldom seen (e.g., Gentner, 1987), Heuer (1988, 1991; Heuer & Schmidt, 1988) has argued that the pervasive tendency toward approximately proportional scaling supports the notion of the GMP. Most important, the GMP and recall schema were proposed as independent memory representations that could presumably be learned independently of each other. That is, although how GMPs are learned is not addressed in schema theory—their existence is presumed—the theory contains important predictions regarding the learning of recall and recognition schemata.

The notion that the GMP, which governs the structure of the movement, and the recall schema, which governs the scaling of the response, are based on independent memory states is important for both theoretical and practical reasons. Theoretically, the notion of independent memory states seems to be supported by a relatively large body of evidence (to be discussed later in this article) and is a central feature of a number of other theoretical perspectives. The distinction between GMPs and movement parameters is similar in kind to the structural and metrical characteristics of a task in the dynamical systems perspective (Kelso, 1981; Newell, 1981). Other theorists have described the relative (i.e., GMP) and absolute (i.e., parameter) characteristics of motor responses, respectively, as higher and lower order variables (e.g., Fowler & Turvey, 1978) and as essential and nonessential variables (Gelfand & Tsetlin, 1971; Kelso, Putnam, & Goodman, 1983; Langley & Zelaznik, 1984). More recently, Keele, Jennings, Jones, Caulton, and Cohen (1995) and Verwey (2001) have viewed movement sequences in terms of independent, perhaps parallel, processing mechanisms: one processing mechanism responsible for planning and organizing the elements in the sequence and the other responsible for the articulatory activities required to effect the planned action. Verwey, for example, proposed a cognitive processing mechanism that plans and represents the sequence and a motor processing mechanism that formulates the specific commands required to carry out the desired sequence. An interesting feature of Verwey's dual-processor model is the proposal that the cognitive and motor processing mechanisms are not only independent but can operate in parallel. From a practical standpoint, the independence of those constructs is important because practice conditions that enhance or detract from the learning of the response may differentially affect the response structure (GMP) and the scaling of the response (parameters). Indeed, evidence to be presented later in this article makes a strong case that some typical practice schemes (i.e., knowledge of results [KR] manipulations, contextual interference) enhance one aspect of the task (e.g., parameter specification) while disrupting the development of the other (e.g., GMP). What is ultimately needed are practice conditions designed to enhance the development of both the movement structure and the specification of the movement parameters (see Lai, Shea, Wulf, & Wright, 2000).

A fundamental prediction in schema theory is that variable practice within a class of movements (i.e., practice in parameter selection for the GMP) enhances the learner's ability to assign parameters in future situations. That is, compared with constant (or limited variability) practice experience, variable parameter practice facilitates the development of a schema rule. The schema rule has been conceived of as the relationship (regression line) between the movement outcome (e.g., distance an object was thrown) and the parameter (e.g., amount of force) selected under a given set of initial conditions (e.g., weight of the object). Thus, in comparison with constant practice, variable practice should facilitate the selection of novel parameters by enhancing the schema (abstract) rule governing parameter selection.

Another interesting feature of schema theory is the assumption that GMPs are abstract representations that do not include the specification of the effectors used to execute the movement (also see Keele et al., 1995; Verwey, 1999). Rather, the effectors or muscle groups are considered a selectable movement parameter that must be specified before execution. Thus, one can execute movements governed by the same GMP with different effectors (e.g., write one's signature with the dominant hand, nondominant hand, mouth, or foot) with limited, if any, degradation in the relative movement characteristics.

In the following sections, we review the evidence for and against the validity of those assumptions, as demonstrated by research over the last 10 years or so. We begin by reviewing different performance measures that have been used by investigators to describe proficiency in producing the fundamental movement pattern (GMP) versus proficiency in parameterizing the movement to meet specific environmental demands.

Empirical Findings

Measurement of GMP and Parameter Performance

Sequential timing tasks with specified goal relative- and absolute-timing requirements (time between key presses) have been used in a number of investigations conducted in the last few years concerning issues related to schema theory. In other studies, movement-patterning tasks were used, in which a lever, joystick, or force transducer had to be manipulated in a certain predefined spatiotemporal or force–time pattern. We describe in turn the error measures for GMP and parameterization accuracy used in those two cases. We feel that partitioning response errors into independent measures that are attributable to the GMP (relative characteristics) and the parameterization (absolute characteristics) of the response is important to understand the control processes that change over the course of training and learning. That is especially important because recent studies have shown that some factors that negatively affect the learning of the GMP have positive effects on parameterization learning, and vice versa. Those measurements also allow a relatively independent assessment of the movement production problems associated with the GMP and parameter specification—problems that are clouded when overall error measures are used.

Sequential key-press tasks. Several investigators (e.g., Badets & Blandin, 2004; Black & Wright, 2000; Blandin, Lhuisset, & Proteau, 1999; Lai & Shea, 1998, 1999; Lai, Shea, Wulf, et al., 2000; Wulf, Lee, & Schmidt, 1994) have used serial key-press tasks in which participants were asked to depress a sequence of keys (e.g., 2, 4, 8, 6 on the numeric keypad) on a computer keyboard. Typically, there were goal movement proportions for each segment (percentage of time between key presses to total time). In addition, when different task versions were practiced, the goal relative timing between segments remained constant (e.g., 22.2%–44.4% –33.3%) while the overall duration was varied. Relative-timing performance was usually measured as the sum of the absolute differences between the goal proportions and the actual proportions for each segment. That error measure has been termed *relative timing* (AE_{prop}; e.g., Wulf et al., 1994). To assess absolute-timing performance, one uses various error measures (e.g., constant error, absolute constant error, variable error, or total error) to characterize the deviation of the actual overall movement time from the goal movement time. Thus, relative errors (e.g., AE_{prop}, residual *RMSE*) provide measures of the GMP, and the absolute error measures provide independent measures of parameter selection.

Movement-patterning tasks. A typical error measure used to determine the accuracy of a movement waveform in relation to a goal waveform is total root-mean-square error (total *RMSE*; e.g., Schmidt & Lee, 1999; Wulf et al., 1993). In essence, total *RMSE* indicates how closely the waveforms produced by the participants match the criterion waveform (see Figure 2, top). Because that measure is sensitive to both errors in the GMP and errors in parameterization, however, researchers have partitioned total *RMSE* into separate measures for GMP and parameter performance. As a measure of GMP performance, residual *RMSE* is used. The term *residual RMSE* was first used by Wulf et al. (1993) to indicate errors that remain after one mathematically corrects for errors in scaling the movement (e.g., absolute force and time). Residual *RMSE* is calculated as the *RMSE* between the participant's waveform and the criterion waveform, the latter of which is rescaled so that any force or time parameter errors can be eliminated (see Figure 2, bottom). The rescaling procedure involves the search for the best fit between the produced and the criterion waveforms by systematically "shrinking" or "stretching" the criterion waveform in time and amplitude (for a description of the exact procedure, see Whitacre & Shea, 2000, 2002; Wulf et al., 1993). Because the difference between the rescaled criterion waveform and the participant-produced waveform is void of parameter errors, residual *RMSE* is used as an estimate of errors in the movement structure (i.e., GMP error).

One determines parameter errors by calculating the difference in the parameters (time and amplitude) between the original criterion pattern and the parameters for the rescaled criterion waveform. The force and time parameters associated with the rescaled criterion represent the parameters that best fit the participant's movement.

GMP and Parameter Learning

Factors affecting GMP learning. A number of researchers have used relative-timing errors (AE_{prop}) or residual *RMSE*, depending on whether the movement was evaluated on the basis of discrete (Wulf, 1992; Wulf et al., 1994) or continuous (Whitacre & Shea, 2002; Wulf & Schmidt, 1989; Wulf et al., 1993) analyses, to infer GMP performance and learning. In addition, Sekiya et al. (1996; Sekiya et al., 1994) have used relative mean velocity to characterize GMP performance in their experiments. Those measures of GMP errors provide a ratio scale assessment of the participants' deviations in the relative timing, the force pattern, or both, from the specified (goal) relative pattern, which are useful in determining the subtle changes that occurred in the GMP across practice and in response to experimental manipulations. Specifically, those measures of GMP performance appear to be sensitive to manipulations of segmental complexity (Park & Shea, 2003b, in press; Wright & Shea, 2001), practice (Whitacre & Shea, 2002), reduced KR frequency (Lai & Shea, 1998; Lai, Shea, Bruechert, & Little, 2002; Wulf, 1992; Wulf et al., 1993), bandwidth KR (Lai & Shea, 1999; Lai et al., 2002), contextual interference (Sekiya et al., 1996; Sekiya et al., 1994; Wright & Shea, 2001; Wulf, 1992; Wulf & Lee, 1993), observation–modeling (Badets & Blandin, 2004; Black & Wright, 2000; Blandin et al., 1999; Lai, Shea, & Little, 2000; Shea, Wulf, Park, & Gaunt, 2001), and the nature of

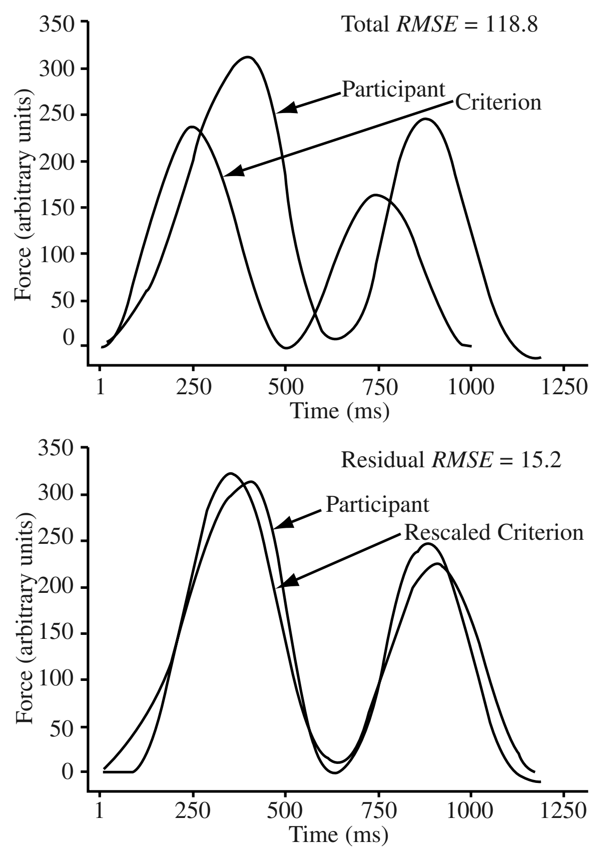

FIGURE 2. Example of the participants' and the goal waveforms. The difference between the original waveforms (top) is total root-mean-square error (Total *RMSE*). Residual *RMSE* is the difference between the rescaled goal waveform and the original participants' waveform.

the feedback (relative vs. absolute) provided (Wulf, Lee, & Schmidt, 1994).

Most important, Lai and colleagues (e.g., Lai & Shea, 1999; Lai, Shea, Wulf, et al., 2000; also see Whitacre & Shea, 2000, 2002) have consistently demonstrated across a number of experimental manipulations that, when practicing a single relative-timing pattern, factors that promote trial-to-trial consistency in production of that pattern enhance relative-timing (GMP) learning, at least early in the learning process. One achieves trial-to-trial consistency by using constant or blocked practice versus serial or random practice, with variability created by changing parameter values; reduced KR frequency versus 100% KR in variable practice; and bandwidth KR in variable practice. The finding that increasing trial-to-trial consistency during acquisition is beneficial to GMP development is illustrated in Figure 3 (top) and has been termed the *stability hypothesis* by C. H. Shea, Lai, et al. (2001). One can achieve the increased consistency either by reducing the number of required trial-to-trial changes in parameterization (constant, blocked practice) or by making the parameter changes more predictable (serial practice). Note that residual *RMSE* is smaller for the constant practice group than for the variable practice (blocked, serial, random) groups. Furthermore, GMP learning decreases systematically as a result of how the parameter variability is organized during practice. That is, residual *RMSE* increases from blocked practice to serial practice and again in random practice, although each of those conditions consists of the same amount of absolute variability. Clearly, the manner in which parameter variability is scheduled affects the learning of the GMP.

Most interesting, the metric in which the experimenter presents the segment goals and feedback and that defines the relative-timing pattern has a profound effect on the learning of the GMP. Consider, for instance, a sequential timing task in which the goal movement times (MTs) between consecutive key presses are 200-400-300 ms (e.g., Lai, Shea, Wulf, et al., 2000). In that example, the total MT would be 900 ms. The goal segment MTs can be presented to participants in terms of absolute numbers (200-400-300), and feedback would be provided in a similar format (e.g., 185-463-350) as in Wulf and Lee (1993). Alternatively, the goal MTs could be presented in terms of percentages of the total MT (22.2%-44.4%-33.3%–900 ms), with the last number indicating the total MT. In that case, feedback about the segments' MTs would also be provided in percentages (e.g., 22.4%-45.0%-32.6%–1,120 ms) as in Lai, Shea, Wulf, et al. Typically, three versions of that task are practiced, all of which share the same relative timing but vary with regard to the overall MT (e.g., 700, 900, 1,100 ms). More important, the schedule on which the three tasks are practiced affects learning of the relative-timing pattern, but its influence depends on whether the goal MTs and feedback are presented as absolute numbers (milliseconds) or ratios (percentages). Specifically, serial and random practice have been shown to retard learning of relative timing if segmental goals are presented as ratios (e.g., Lai, Shea, Wulf, et al.) but to enhance relative-timing learning if they are presented as absolute values (e.g., Wulf & Lee). The opposite is true for constant and blocked practice (even though variability is introduced in blocked but not in constant practice). Lai and colleagues (e.g., Lai & Shea, 1999; Lai, Shea, Wulf, et al.; C. H. Shea, Lai, Wright, Immink, & Black, 2001) have argued that providing ratio goals (and feedback) is helpful for relative-timing learning in blocked practice because cog-

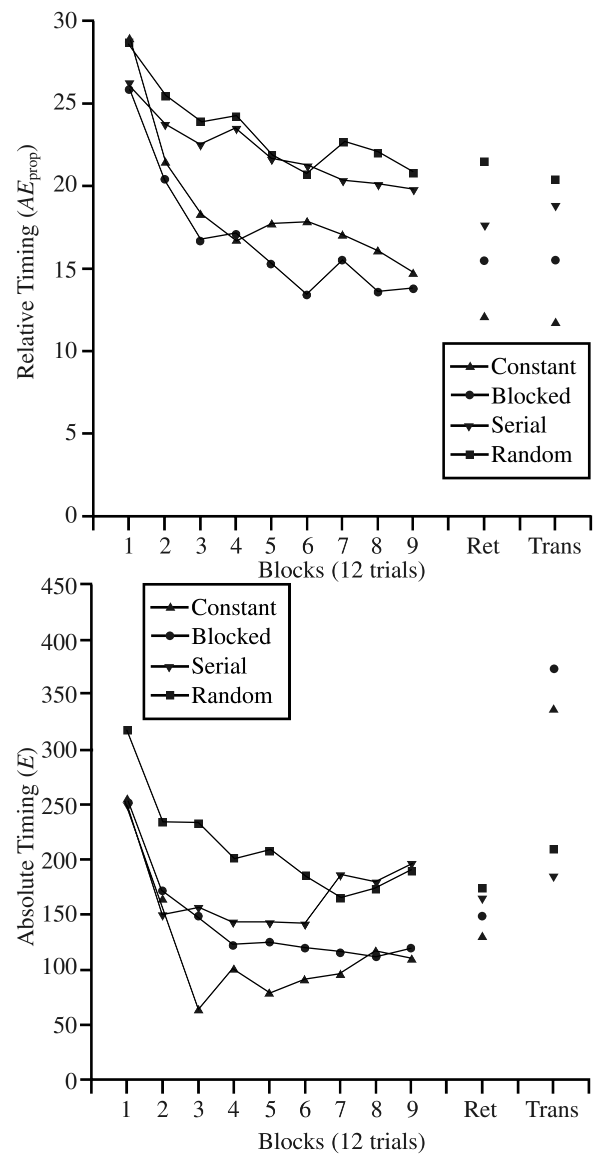

FIGURE 3. Top. Relative-timing performance for constant, blocked, serial, and random practice groups. **Bottom.** Time parameter errors. Note that relative-timing learning was best for the constant and blocked groups, whereas absolute timing was best for the serial and random groups. From C. H. Shea, Lai, Wright, Immink, & Black (2001), Consistent and variable practice conditions: Effects on relative and absolute timing, *Journal of Motor Behavior, 33*, 139–152. Copyright 2001 by Heldref Publications, Inc.

nitive demands are generally thought to be relatively low in that condition. Ratio goal (and feedback) may overwhelm participants under random practice conditions, however, because cognitive demands are relatively high. Thus, relative-timing learning may be sacrificed when additional cognitive demands (segment ratios) are added to the already high demands imposed by random practice. In contrast, in blocked practice, sufficient cognitive resources are available to translate the ratio information, and segments ratios may explicitly communicate the common features of the task variations, thereby enhancing relative-timing learning. In fact, ratio information may promote interitem processing (J. B. Shea & Morgan, 1979; J. B. Shea & Zimny, 1983, 1988.

Factors affecting parameter learning. Schmidt (1975, 1985; Schmidt & Lee, 1999) proposed that the recall schema, which governs parameter specification, is strengthened as a function of variable parameter practice. Variable practice was thought to provide the participant with a wider range of specified parameters and associated movement outcomes that were abstracted to form the rule for specifying future parameter requirements (i.e., recall schema). That notion led to the variability of practice hypothesis whereby an increased range of parameter experiences was thought to enhance the determination of the rule for accurately specifying the parameter. The findings resulting primarily from a flurry of experiments following the proposal of schema theory in 1975 indeed provide relatively strong support for that notion (e.g., Carson & Wiegand, 1979; Kelso & Norman, 1978; Kerr & Booth, 1978; Margolis & Christina, 1981; McCracken & Stelmach, 1977; Moxley, 1979; Newell & Shapiro, 1976; C. H. Shea & Kohl, 1990, 1991; C. H. Shea, Kohl, & Indermill, 1990; Wrisberg & Ragsdale, 1979; Wulf, 1991; for a review, see Shapiro & Schmidt, 1982). When compared with constant practice, variable practice generally resulted in more effective parameter specification in retention or transfer. Yet, the variable practice advantages were typically greater in studies of children than in studies of adults. Shapiro and Schmidt suggested that the variability of practice hypothesis might therefore best be tested in children because parameter specification rules would still be in the formative stage (also see Schmidt, 1985).

An interesting and consistent finding in newer studies (e.g., Lai, Shea, Wulf, et al., 2000; C. H. Shea, Lai, et al., 2001; see also Wulf, 1991) has been that the effectiveness of variable practice is a function of how the variable practice session is scheduled. Specifically, compared with constant or blocked practice schedules, serial or random practice schedules have been shown to be conducive to absolute-timing learning, at least as indicated by transfer performance (i.e., when novel parameters are required; see Figure 3, bottom). That is, when absolute-timing requirements change from to trial to trial, as is the case for serial or random practice formats, absolute-timing learning is enhanced in comparison with situations in which absolute-timing requirements generally do not change from trial to trial, as in constant or blocked practice. Thus, in addition to the range of practice variability, the scheduling of the variability appears to have a profound effect on parameter learning.

The finding that the scheduling of the variable practice session influences parameter learning contradicts a strict interpretation of the variability of practice hypothesis that was a direct outgrowth of schema theory (Schmidt 1975, 1988). According to the hypothesis, the ability to parameterize a movement sequence is a product of the range of practice variability without regard to the scheduling of the variability. Nevertheless, an important contribution of schema theory is the proposition that practice variability in parameterization should be more effective than constant practice for parameter learning.

In addition, a number of factors that affect GMP learning have been found to have no, or sometimes even opposite, effects on parameter learning. For example, absolute-timing (parameter) learning appears to be relatively unaffected by manipulations of relative-timing feedback (Lai, Shea, et al., 2000; Wright & Shea, 2001). Similarly, a number of researchers (Lai & Shea, 1998, 1999; Wulf, 1992; Wulf et al., 1993) have consistently demonstrated that manipulations of reduced frequency or bandwidth relative-timing KR have little, if any, effect on absolute-timing learning, although Bruechert, Lai, and Shea (2003) provided evidence that parameter error detection may be enhanced under reduced KR frequency conditions. In addition, Wulf et al. (1994) have demonstrated that, compared with 100% absolute-timing KR frequency, reduced frequency of absolute-timing feedback does not influence absolute-timing errors.

Although variable practice is typically beneficial to the learning of the parameter that is varied, other movement parameters may be negatively affected (e.g., Whitacre & Shea, 2000, 2002). In Whitacre and Shea's (2000) study, for example, participants had to learn a force-production task with specific force as well as time requirements. When one parameter (e.g., absolute force) was varied in practice, variable practice had a detrimental effect on the learning of the other parameter (e.g., absolute time). It is possible that learners directed more attention to the (variable) force parameters at the expense of learning the correct time parameterization. In those experiments (Whitacre & Shea, 2000, 2002), parameter specification—particularly the specification of a parameter that was not varied in practice—was relatively unstable, deteriorating substantially from acquisition to retention. The instability was also evident on a transfer test: Transfer to a new force (varied parameter) requirement disrupted the timing (nonvaried parameter) parameter. The bottom line may be that dealing with parameter variability while trying to formulate a rule for a second independent parameter, or while still formulating the GMP, may be overwhelming from a processing standpoint (see Wulf & Shea, 2002). Thus, variable practice seems to result in clearer parameter-learning advantages than constant practice does, especially when variability is scheduled in a random, as opposed to blocked, format, but that benefit may be associated with some negative side effects.

Empirical Disassociation Between GMP and Parameters

Evidence Suggesting Dissociation of Memory States

A general tenet of Schmidt's schema theory (1985, 1988) is that the theoretical constructs, GMP and parameter (or parameters), that govern programmed actions are controlled by separate memory states. Until recently, the major evidence in support of that dissociation was that movements could be varied along temporal, spatial, or force dimensions, whereas the structure of the movement remained essentially invariant (Gentner 1987; Heuer, 1988; Schmidt, 1985; see Wulf et al., 1993, for a discussion of dissociation). In more recent experiments, however, beginning with Wulf and Schmidt (1989), performance has been partitioned into relative timing, relative force, or relative spatial error (i.e., measures of GMP error), and absolute time, absolute force, or absolute spatial error (i.e., measures of parameter error). Those experiments have consistently demonstrated that some factors that affect the learning of the relative-timing pattern either do not affect absolute-timing learning or may even affect absolute-timing learning in the opposite direction. Consistent with that position, Lai, Shea, et al. (2000) recently demonstrated empirically that relative- and absolute-timing errors were not correlated with each other, but were highly correlated with a global error measure. A regression analysis of the data of the Lai, Shea, et al. study, in which practice schedule (constant and serial) and KR condition (50% and 100% relative KR frequencies) were manipulated, confirmed that relative- and absolute-timing errors independently contributed (i.e., statistically) to the global error measure. That is, relative and absolute-timing errors together accounted for 95% and 98% of the variance in the global error measure in Experiments 1 and 2, respectively, but were not significantly correlated with each other.

Additional evidence for the dissociation of GMP and parameter processes comes from a recent study by Wright and Shea (2001; also see C. H. Shea & Park, 2003b, in press). They asked participants to produce a sequence of four keystrokes (three intervals) with a goal relative-timing pattern of 33%, 33%, and 33%, which was labeled a *simple pattern*, or a goal relative-timing pattern of 22.2%, 44.4%, and 33.3%, which was labeled a *complex pattern*. They found that participants were quite good at producing the simple relative-timing pattern, even early in practice (which could have afforded them more opportunity and processing resources that could have been devoted to develop the parameter scaling rule). Alternatively, the complex relative-timing pattern was continually improved over practice, with participants in that condition never reaching the relative-timing proficiency of the participants in the simple relative-timing pattern condition. Absolute timing for the two groups was similar, however. Wright and Shea concluded although it had substantial impact on relative-timing learning (Figure 4, top), making the relative-timing structure more or less difficult, did not affect the resultant absolute-timing errors (Figure 4, bottom).

Taken together, those findings provide strong support for the empirical dissociation of the memories governing GMP and parameter learning. A goal in future research should be

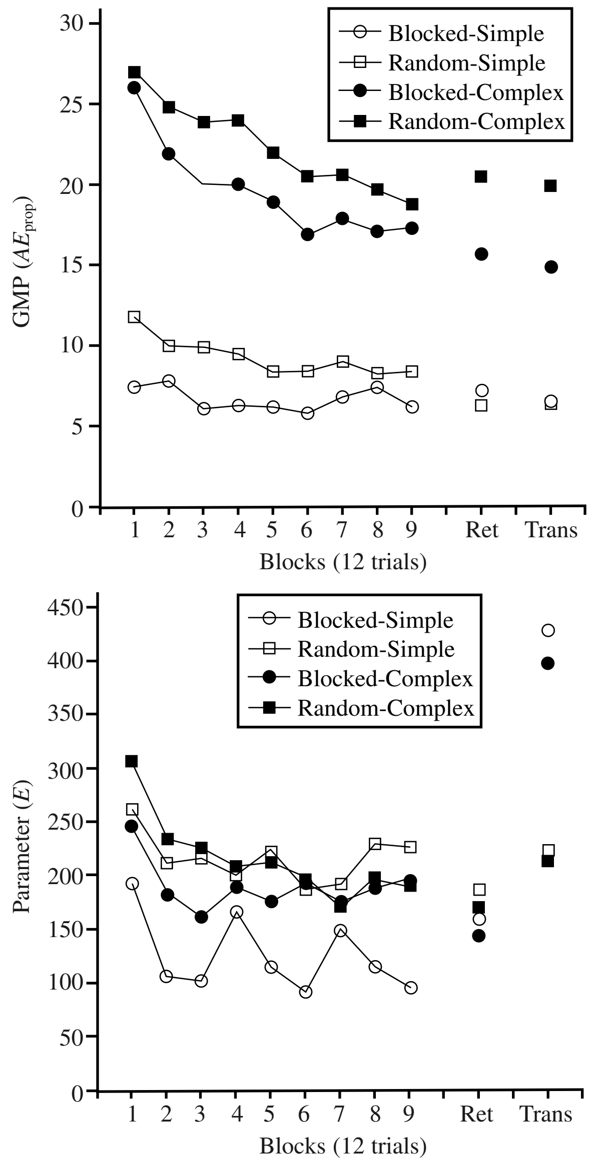

FIGURE 4. Top. Relative-timing performance, generalized motor program (GMP; AE_{prop}), for blocked (open symbols) and random (closed symbols) practice groups. Circles represent performance for simple timing task with a 33%, 33%, and 33% goal relative-timing pattern, and squares designate complex timing tasks with 22.2%, 44.4%, and 33.3% goal relative-timing pattern. **Bottom.** Time parameter errors (E). Note that relative-timing errors were smaller for the simple task but that absolute-timing errors seemed to be unaffected by the relative-timing complexity. Data used with permission from D. L. Wright and C. H. Shea (2001), Manipulating generalized motor program difficulty during blocked and random practice does not affect parameter learning, *Research Quarterly for Exercise and Sport, 72,* 32–38. Copyright 2001 by American Alliance for Health, Physical Education, Recreation, and Dance.

determining factors (e.g., practice schedule, feedback condition) that can optimize both relative- and absolute-timing learning (see Lai et al., 2002; Park, Shea, & Wright, 2000; C. H. Shea et al., 2001). To date, many of the manipulations that have been experimentally tested have resulted in the enhancement of either the relative or absolute timing but rarely both, and often improvement in one is achieved at the expense of the other. One could perform a more stringent test of dissociation or separability of memory states, which was not proposed in schema theory and has not been tested, by assessing the degree to which individuals can apply an absolute-timing (parameter) rule developed, for example, on the basis of one relative-timing pattern (GMP) to a novel movement that has a different relative-timing structure. If the memory states that give rise to the GMP and parameter specification are truly independent rather than separate or dissociated from each other, then participants should be effective in applying a parameter rule developed during practice with one class of movements to a new task with a different relative-timing pattern.

As noted in the introductory comments, it is important to recognize that in a number of other theoretical perspectives, the empirical dissociation between the structure of the movement and the activation of the specific effectors has been proposed and examples have been provided (e.g., Keele et al., 1995; Klapp, 1995, 1996; Verwey, 1999; see also Keele, Cohen, & Ivry, 1990; Sternberg, Knoll, & Turock, 1990, for a discussion). It has been proposed in those perspectives that the processing, programming, and production of response sequences, alone or in combination, depending on the theoretical perspective, are independent of those required for producing the elements comprising the sequence. Those commonalities are important theoretically because notions of hierarchical or modular processing and programming components, or both, are central to many current models of sequence production (e.g., Keele et al., 1990; Verwey) but are not necessarily restricted to the notion of a motor program.

The Interdependence of GMP and Parameter Memory Development

In the previous subsection, we argued that there is substantial suggestive evidence of a dissociation between the memory states that govern relative and absolute timing. It is also clear, however, that the way parameter variability during practice is structured (blocked, serial, or random practice) does affect the learning of the GMP—even though the relative-timing requirements (GMP) may be kept constant. Thus, the variability created in many experiments by changing the absolute-timing requirements has substantial influence on relative-timing learning. That is, constant, blocked, serial, and random practice, as in C. H. Shea, Lai, et al. (2001), for example, all resulted in constant practice on the relative-timing pattern (they created and scheduled variability by manipulating absolute timing). That finding suggests that manipulation of absolute timing, which directs the learner to compress or stretch a movement along a parameter dimension without changing the relative characteristics of the movement, influences relative-timing (GMP) learning. Thus, it appears that relative- and absolute-timing processes are governed by separate memory states but may be interdependent in terms of the development of those memory states.

In summary, there appears to be strong evidence, on the basis of a number of manipulations and measurement schemes, consistent with the notion of independence of the GMP and parameters. The evidence comes not only from experiments conducted to test the schema theory notions but also from the sequence-learning literature. It does appear, however, that manipulating parameter variability during practice while holding the GMP constant affects the learning of the GMP.

Effector Transfer

One of the initial proposals of schema theory was that the effectors (i.e., muscle or muscle groups) that are used to produce the movement are selectable in much the same way as other absolute characteristics (e.g., absolute time, absolute force) of the response are selected before movement execution. That proposal is quite different from many of the earlier notions of motor programs (e.g., Henry & Rogers, 1960) in which it was implied that the muscle activation patterns are directly controlled by the motor program. In reference to Merton's (1972; also see Raibert, 1977) demonstration that individuals can produce the same signature on a check or 10 times larger signatures on a blackboard, Schmidt (1975) stated that schema theory explains that phenomenon by proposing that a GMP requires certain specifications to produce a given movement sequence that meets a unique set of environmental constraints. Those later became known as the variant (selectable) characteristics of the motor program (e.g., absolute time, absolute force, and specific effectors), which were contrasted with the invariant characteristics (e.g., order of the elements, relative time, relative force) that defined the GMP. The ability to effectively select new effectors is the focus of the following section.

Although Merton (1972) and Raibert (1977) provided interesting demonstrations that individuals can produce their signature by using different muscle groups, there was no attempt, other than visual inspection, to determine the degree to which the signatures matched. Some years later, Wright (1990) and Castiello, Stelmach, and Lieberman (1993) provided careful kinematic analyses of handwriting by participants who used different effectors, and generally concluded that there were striking similarities in the shape of the letters but also some important differences across muscle groups. Thus, that important prediction of schema theory, which has come to be known as *effector independence*, had not been systematically studied—until recently. The more recent attempts to study that prediction were prompted not only by schema theory but also by recent theoretical perspectives in which the memory state or processing mechanism—depending on the theoretical perspective—responsible for organizing elements in a sequence is proposed to be more abstract than the memory state or processing mechanism responsible for the direct articulatory activities that produce the movement outcome (Keele et al., 1995; Verwey, 1999; also see Klapp, 1996; MacKay, 1982). In addition, researchers using the dynamical system perspective have studied that question (Buchanan, 2004; Kelso & Zanone, 2002), noting, like researchers from more cognitively oriented perspectives, that high-level dynamic representation of skilled behavior proves to be largely effector independent. In the next subsections, we briefly outline some of the recent effector transfer experiments.

Recently, Park and Shea (2002), in an attempt to begin the process of systematically studying effector transfer, allowed participants to practice producing a force–time waveform with one set of effectors. They then compared delayed retention performance of participants who used the same set of effectors with performance on a transfer test in which a different set of effectors was required. In Experiments 1 and 2, contralateral or ipsilateral effector transfer tests were conducted. The contralateral test involved transfer to the opposite limb, whereas the ipsilateral effector transfer test involved transfer in which the agonist and antagonist muscles switched roles. In Experiment 3, participants practiced the static, force-production task used in Experiment 1. After completing the delayed retention test, participants were asked to produce a dynamic version of the task. That transfer condition involved considerably different muscle activation patterns, but the relative-timing and relative-force requirements were the same.

The results were remarkably similar across the three experiments, regardless of whether transfer was to a new limb (see Figure 5), a different muscle group on the same limb, or from static to dynamic versions of the task. Under all conditions, GMP performance was maintained across the effector transfer test, but the specification of force was not. Those effects were virtually the same regardless of which condition (left or right hand; triceps-push or biceps-pull) the participant practiced under. The data suggested that the movement structure (GMP) was stored in an abstract, effector-independent manner, whereas force parameterization was specific to the muscle group used during practice. Most interesting, that result has been replicated by Park and Shea (in press), who used a 16-element arm-movement sequence. After 1 day of practice with the right limb, participants were able to effectively produce the movement pattern with their left limb. Likewise, using a temporal pattern of key presses, Lai et al. (2002) found that participants could produce nearly identical relative-timing patterns when the role of the fingers was reversed, different fingers were used, or when a single finger was moved from key to key. Those results provided strong empirical support for the notion of effector independence, at least with respect to the movement structure (GMP), and are consistent with the notions proposed in schema theory, whereby the specification of the effectors is treated like any other movement parameter that must be specified before execution. Those findings are also consistent with the proposal that independent computational modules are responsible for sequence and element production (Keele et al., 1995) and the notion of independent cognitive and motor processing mechanisms (Verwey, 1999). According to both perspectives, the computational module or processing mechanism responsible for organizing the sequence characteristics of the response do so in a more abstract manner than does the module or mechanism responsible for formulating the specific motor commands. Similarly, Kelso and Zanone (2002) have argued that coordination dynamics and associated changes in task-level attractor states are represented at an abstract, effector-independent level of system functioning. Regardless of the theoretical perspective, the bottom line is

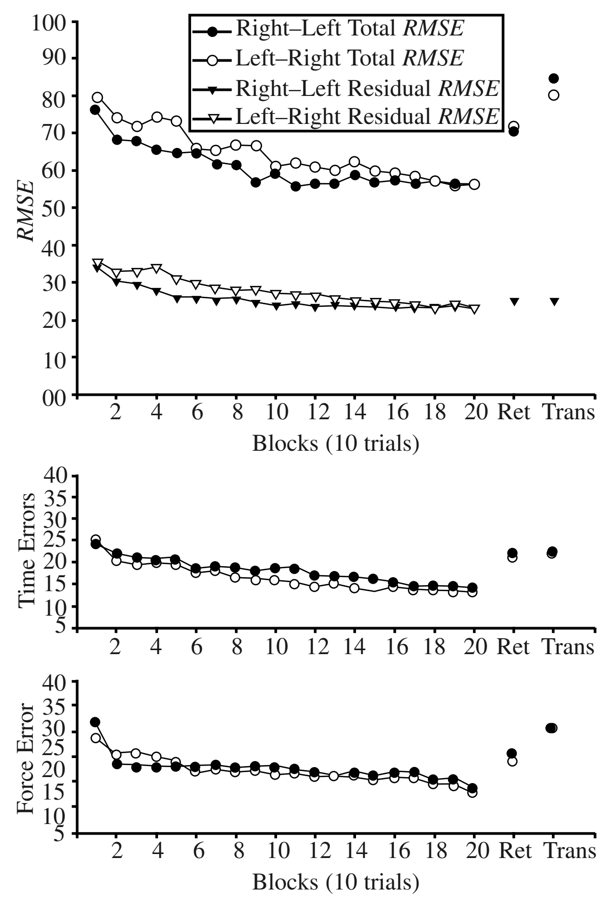

FIGURE 5. Top. Total root-mean-square error (*RMSE*), which characterizes generalizable motor program (GMP) and parameter errors, and residual *RMSE*, which isolates GMP errors. **Middle and bottom panels.** Time and force parameter errors, respectively. From Experiment 1, of J.-H. Park and C. H. Shea (2002), "Effector Independence," *Journal of Motor Behavior, 34,* 253–270. Copyright 2002 by Heldref Publications, Inc.

that at least some characteristics of movements are represented in an abstract, effector-independent manner.

Although Park and Shea (2002, in press) have demonstrated in a number of recent studies that the relative characteristics of simple movement sequences can be effectively transferred to new muscle groups, Park and Shea (2003a) conducted another experiment to determine the effect of practice on the extent to which simple response sequences practiced with one set of effectors could be effectively produced with a new set of effectors. Furthermore, they were interested in whether the relative and absolute characteristics of the task were differentially affected on the effector transfer test after extended practice. Given additional practice, it is possible that in an attempt to optimize movement production, the motor system more directly links effector information to the response structure than appears to be the case early in practice (e.g., Park & Shea, 2002). That general phenomenon has been termed *coarticulation* (Jordan, 1995) and has been shown to influence the production of well-learned movement sequences in speech (e.g., Benguerel & Cowan, 1974), key pressing (Verwey & Wright, 2004), and in skilled typing (e.g., Gentner, Larochelle, & Grudin, 1988). The effect of additional practice, then, would be a more effective response when the same muscle groups are used but of little additional benefit when a new set of effectors is required. In the extended practice experiment, delayed contralateral and ipsilateral effector transfer tests were compared with a delayed retention test (effector transfer tests counterbalanced). The use of contralateral and ipsilateral effector transfer tests in the same experiment also permitted hemispheric- and handedness-specificity questions to be addressed (e.g., Henningsen, Ende-Henningsen, & Gordon, 1995) because the ipsilateral effector transfer task is primarily controlled by the hemisphere and hand used to control the practice and delayed retention tests, and the contralateral effector transfer task is governed primarily by the other hemisphere and hand.

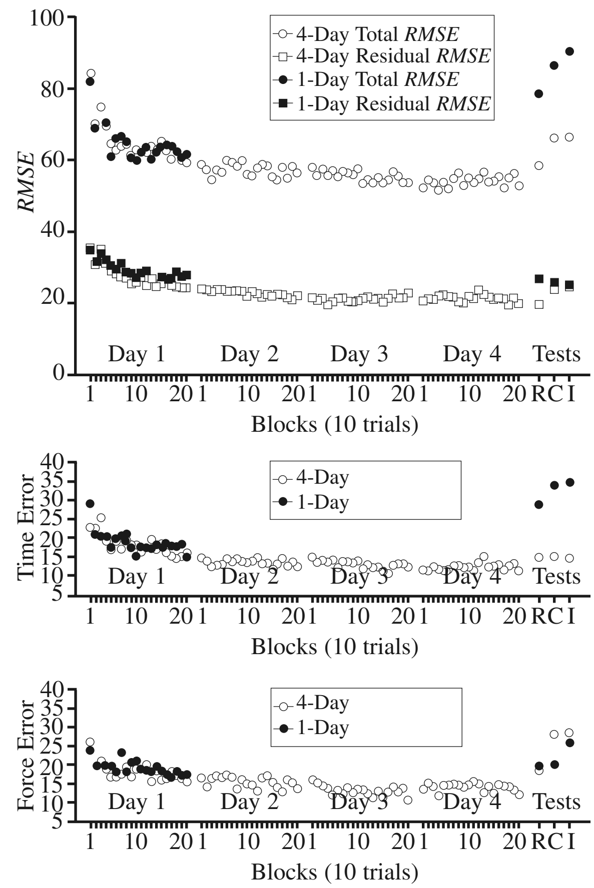

FIGURE 6. Top. Total root-mean-square error (Total *RMSE*), which characterizes generalizable motor program (GMP) and parameter errors, and residual *RMSE*, which isolates GMP errors. **Middle and bottom panels.** Time and force parameter errors, respectively. Filled symbols depict the 1-day practice group and the open symbols the 4-day practice group. From J.-H. Park and C. H. Shea (2003a), "The Effects of Practice on Effector Transfer," *Journal of Motor Behavior, 35,* 33–40. Copyright 2003 by Heldref Publications, Inc.

The acquisition performances of the 1- and 4-day acquisition groups were very similar on all dependent variables on the 1st day of practice, with the 4-day group continuing to refine the movement sequence across the additional 3 days of practice (see Figure 6). Indeed, the retention and transfer results of the 1-day group replicated very closely the results of Park and Shea (2003a). However, those results were restricted to the 1-day acquisition group. After 4 days of practice, not only the measure of parameter performance but also the measure of GMP performance were negatively affected by the effector transfer conditions. That finding suggests that, as the movement sequence was refined during the additional practice, the movement structure became less effector independent than it was earlier in practice (see Shapiro, 1977, for an alternative finding).

Using a 16-element repeated sequence, Park and Shea (in press) also provided evidence that after extended practice, participants structured their response (consolidated or concatenated elements) on an effector transfer test differently than they did on the retention test. That was not the case after one practice session. In fact, the sequence organization that was used on the effector transfer test after extended practice was similar to that observed much earlier in practice. In the Park and Shea (2003a) experiment, the finding that not only the movement structure but also the specification of force were equally effective on the effector transfer tests for the 1- and 4-day groups provided support for that position. Additional practice resulted in a more refined and better scaled movement sequence that was also less adaptable to effector transfer conditions. When participants were faced with producing the response with a different set of effectors, the additional practice resulted in no additional benefit in terms of the response structure and the specification of force. The results of those experiments suggest that the independence of the movement structure and movement scaling may be lost over practice with the movement structure and when the force characteristics become more closely integrated. It seems reasonable that after initial practice with that type of task, participants attempt to exploit the unique characteristics of the specific effectors and that exploitation benefits response production when the same effectors are used but increasingly limits the extent to which the response sequence is effector independent (also see Proteau, Marteniuk, Girouard, & Dugas, 1987; Proteau, Marteniuk, & Lévesque, 1992).

In summary, the present findings suggest that the way in which those types of movements are represented in memory changes across practice. Early in practice, the response structure appears to be represented in a relatively abstract way, as proposed in schema theory, resulting in effector-independent performance capabilities. Later in practice, as muscle-specific characteristics are exploited in an attempt to refine the movement pattern, the response becomes more literally represented, resulting in enhanced performance when the same muscle groups are used but less effective performance when circumstances require the response to be executed with a new muscle group.

GMP Learning

How GMPs are learned is not addressed in schema theory. Rather, their existence is assumed, which has been seen as a limitation of the theory. More recent studies, however, provide some insight into how GMPs are acquired. The results of those studies suggest that GMPs develop over practice—becoming more refined and stable as practice continues. For example, Wulf and Schmidt (1989), using a sequential key-press task with three movement segments, demonstrated a shift in the temporal structure of the movement segments across practice. They found that learners produced relatively similar segment proportions early in practice but gradually approached the goal proportions of the movements as practice progressed. Similarly, Park and Shea (2003b; see Figure 7) recently noted that when participants were asked to produce a sequence of six keystrokes with a difficult goal relative-timing pattern (18.75%, 31.25%, 12.50%, 12.50%, 25%), they initially produced a relatively easy and uniform (see Wright & Shea, 2001) timing pattern (approximately 20%, 20%, 20%, 20%, 20%). Over practice, they attempted to shorten or lengthen the appropriate interval to match the required pattern (also see Lai et al., 2002). Most interesting, the intervals that had to be lengthened or shortened the most were also more variable. As can be seen in Figure 7, Element 2, which required a longer than average interval, tended to be produced too quickly (negative constant error [*CE*]) and was more variable (high variable error [*VE*]) early in practice than Element 1, for example, which was closer to the average interval. Later in practice, the biases and variability were reduced—although there was a tendency for them to reappear on the retention test.

Indeed, Heuer and Schmidt (1988) found that some motor patterns appeared more natural, resulting in a relatively high degree of invariance when the parameters were changed, and that others were less natural, resulting in only a tendency for proportional scaling. Those findings, however, speak directly to the development of new GMPs based on what could be considered primitive GMPs. In that regard, Collier and Wright (1995) found evidence to suggest that complex timing rhythms build on or modify a repertoire of what they called *innate* or *natural timing preferences* (also see Blandin et al., 1999). Kelso and his colleagues (Kelso, 1997; Kelso & Zanone, 2002) suggested that natural timing preferences are a result of what they termed *attractor states*, which can be modified through practice, but at the cost, at least initially, of stability.

Another important question in that context is how GMPs are learned in conjunction with movement parameters. Although schema theory does not speak to that point directly, Roth (1988; also see Lai & Shea, 1999; Lee, Elliott, & Carnahan, 1987) hypothesized and provided evidence that only when a stable GMP has been developed can an effective rule be formulated for specifying parameters. If the GMP is poorly specified early in the learning process, then the parameterization process must also be constantly changing so that changes in the GMP can be compensated—thus inhibiting the development of a stable parameter rule. That notion suggests a hierarchy in the development of programmed actions, with a stable GMP being a requisite for the development of an effective and stable parameter rule. Thus, when the GMP is relatively difficult or very early in practice (even if the GMP is relatively easy), providing learners with constant practice early in acquisition (to enhance GMP learning), with variable practice introduced later in practice (to enhance parameter learning), should constitute an optimal condition for the development of both aspects of movement proficiency. Indeed, Lai, Shea, Wulf, et al. (2000) have provided strong evidence in support of that notion. They found that both GMP and parameter learning were enhanced if constant practice was used during the first half of practice and variable practice in the second half of practice, as compared with the reversed practice schedule or with constant or variable practice throughout the practice period. Providing variable practice throughout acquisition apparently disrupted GMP learning because parameter variability was introduced before the development of a stable GMP (Lai & Shea, 1998). In contrast, parameter learning showed the same beneficial effects as it did when provided throughout the whole practice phase. Thus, if a new GMP has to be learned, parameter variability—at least early in practice—seems to disrupt the learning of a stable GMP.

In summary, if a task requires the learning of both the fundamental movement pattern (GMP) and the appropriate parameterization of the movement, it seems important that learners be given a chance to first concentrate on the basic pattern. Once the movement structure (i.e., relative timing, relative forces) has been developed—preferably through constant practice—and is relatively accurate and stable, one should introduce variability in the scaling of the movement pattern to enhance the parameterization processes. In new

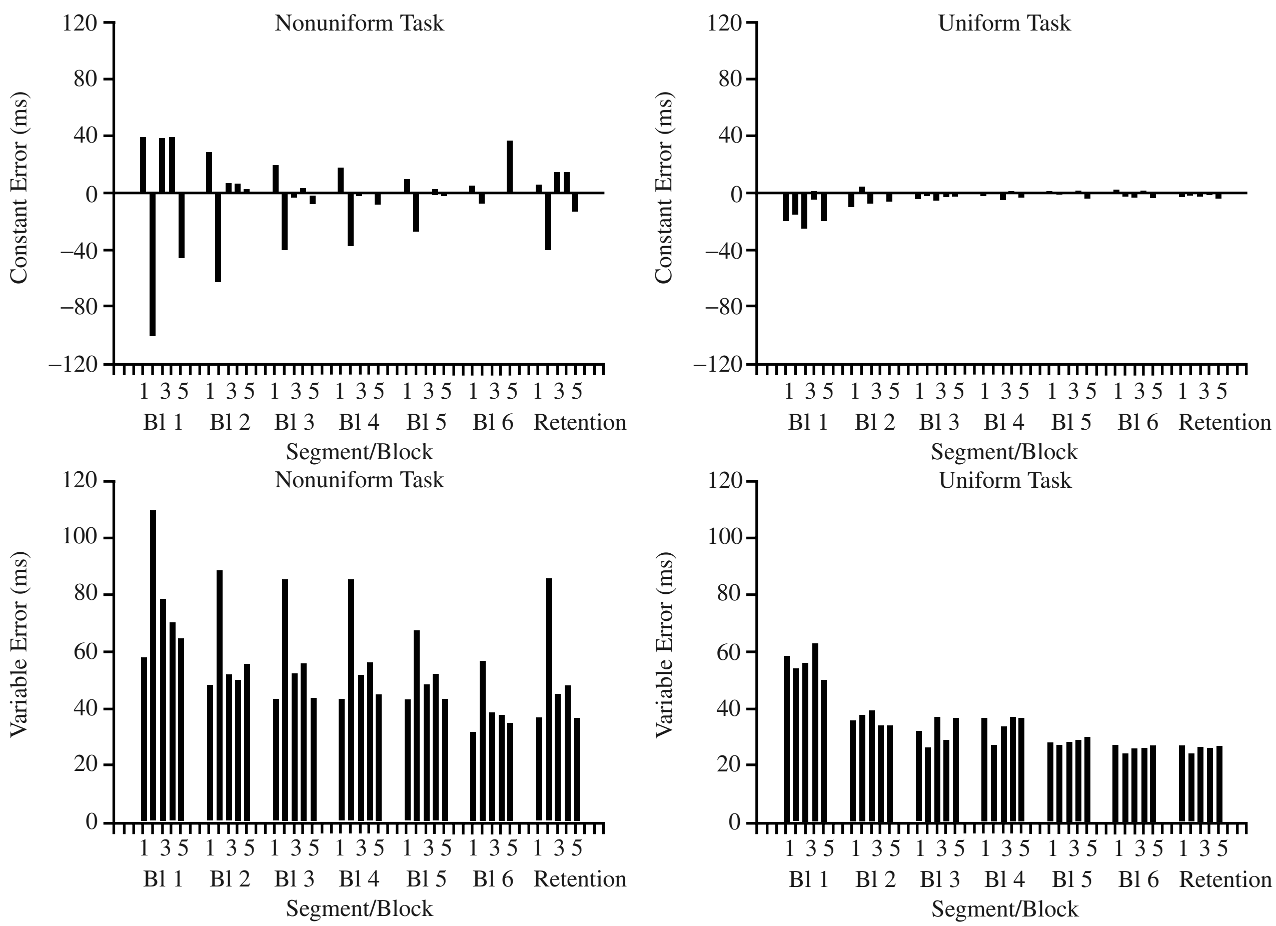

FIGURE 7. Top. Constant (**top**) and variable (**bottom**) errors by elements during acquisition for the nonuniform (left) and uniform (right) tasks in Experiment 3. The uniform task involved a goal relative-timing structure of 20%, 20%, 20%, 20%, and 20% for the five segments. The goal relative-timing structure for the nonuniform task was 18.75%, 31.25%, 12.5%, 12.5%, and 25%. Participants in the nonuniform condition tended to initially produce a uniform pattern—stretching and shrinking the segment times to fit the nonuniform goal pattern over practice. Bl = block. Data used with permission from J.-H. Park and C. H. Shea (2003b), "The Independence of Sequence Structure and Element Production in Timing Sequences," *Research Quarterly for Exercise and Sport, 74,* 401–420. Copyright 2003 by American Alliance for Health, Physical Education, Recreation, and Dance.

conceptualizations of motor skill learning, investigators will need to take into account findings related to GMP and parameter learning and their sequencing. Those and other issues that need to be addressed in future theories are discussed in the next section.

Summary and Future Directions

Schema theory, as originally presented in 1975 and subsequently expanded on by Schmidt in his textbooks and articles, has played an important role in the field of motor behavior. One of its attractions, particularly in more clinical (e.g., occupational and physical therapy) and applied teaching fields (e.g., elementary physical education), has been the strong intuitive appeal of the theory and the easy to comprehend metaphors and analogies that were developed to explain the components of the theory (e.g., record player analogy to illustrate the variant and invariant features, regression line metaphor to illustrate the development of a parameter rule). Although it continues to play a historical role and is cited relatively often, however, most researchers no longer consider the theory a viable theoretical perspective. That change has occurred because some of the fundamental tenets of the theory have not been supported in subsequent research and because of a continued disfavor with the notion of motor programs. Nevertheless, the original theory proposed a number of constructs that have received strong empirical validation. Thus, it is our contention that a viable new theory of motor learning must account for stable findings that have grown out of schema theory research. A new theory is called for, at least in part, by what we view as a void in the ability of current theoretical perspectives to effectively account for the learning and transfer of motor actions. Before suggesting some future research directions, we summarize the findings that were discussed in the body of this article. We then propose some empirical findings that should be accounted for in new theories of motor learning.

Notion of Independent Memory States or Processing Mechanisms

The empirical independence of the movement structure (GMP) and the movement parameters has been demonstrated in numerous experiments. Indeed, we are not aware of any data that suggest otherwise, at least after moderate levels of practice. Although similar distinctions between the organization of the response elements and the specifics of the motor response are provided in other theoretical perspectives, a cogent explanation for the changes that occur over practice, the differential effect of practice conditions of the relative and absolute characteristics of the response, and the ability of individuals to reparameterize or otherwise transfer learned movements are not provided in any of those perspectives. There is some evidence, however, that after extensive practice, independence may be sacrificed in attempts to exploit the specific effectors involved in producing the movement during practice (see Effector Independence section).

Variability-of-Practice Hypothesis

There is quite compelling evidence to suggest that parameter specification is enhanced by variable as opposed to constant practice. Yet, the scheduling of parameter variability during practice—and not just the presence or absence of parameter variability—seems to be an important factor. For example, although variability per se is held constant, the scheduling of variability in a random or blocked manner has been shown to produce differential parameter learning effects. That finding is not in line with a strict interpretation of the "regression line" notion proposed in schema theory, according to which those practice regimens should result in similar parameter rules. Likewise, according to the variability-of-practice hypothesis, the amount and range of practice variability, and not the scheduling of the variability, are considered the critical factors for schema development. Perhaps the retrieval and reconstruction (e.g., Lee & Magill, 1983) and the elaboration (J. B. Shea & Morgan, 1979; J. B. Shea & Zimny, 1983) notions proposed to account for contextual interference effects might provide a more coherent explanation for parameter learning effects.

Furthermore, there are some costs that must be weighed when one considers the benefits of introducing parameter variability. In scheduling parameter variability during practice, the investigators must be concerned with its influence on other parameters that are not varied and on the development of the GMP. Both influences can be negative. They may diminish or even eliminate those negative effects, however, by introducing parameter variability after a stable GMP has been developed. They could accomplish that by structuring practice conditions so as to enhance the GMP early in practice (e.g., by providing constant practice) and introducing random parameter variability later in practice to enhance parameter learning.

Effector Independence

As suggested in schema theory, current experimental evidence indicates that the GMP is stored in a relatively abstract, effector-independent form early in practice. At that stage, performers are capable of effectively executing responses with different muscle groups and different activation patterns. Later in practice, as the learner attempts to refine the movement by exploiting the unique characteristics of the specific effectors, response capabilities become less effector independent. That finding may suggest that the rules governing the generalizability of actions may change over practice, with a relatively large degree of adaptability found early in practice and greater specificity later in practice. That notion requires, however, that investigators conduct additional research to determine if parameter variability (or even effector variability) plays a role in maintaining the response flexibility observed early in practice. It is also important to determine if other schema predictions fail after extended practice. It is entirely possible that the nervous system is configured to provide generalizability and flexibility early in practice so that it can facilitate the learning of new skills and adaptability to new situations but that capability is diminished as higher levels of skill are developed.

Reliance on Motor Program Notions

Schema theory was proposed as an open-loop (motor program based) theory of motor skill control and learning. Thus, in many of the early investigations of the predictions of the theory, researchers used rapid discrete responses—that is, responses with durations of 250 ms or less—in an attempt to minimize feedback-based corrections that presumably would contaminate the results. That delimitation provided contrast to the predominant theory of the day (Adams's, 1971, closed-loop theory) but also provoked considerable debate related not only to the constructs of the theory but also more generally to the notion of motor programs. That debate is clearly seen in recent comments on schema theory by Newell (2003); an entire section of his article is dedicated to the inadequacies of the motor program metaphor. On the other side, Schmidt (2003) countered those objections by citing evidence that agonist and antagonist muscle activation sequences of relatively short duration (e.g., 300 ms) continue to be elicited even when the movement of the limb is unexpectedly restrained (Wadman, Denier van der Gon, Geuze, & Mol, 1979). That finding must be taken as strong evidence that a prestructured plan (motor program) is responsible for the muscle activation sequence. Most interesting, however, an advantage of variable practice over constant practice, for example, has been found for tasks that were as long as 10 s in duration (Wulf & Schmidt, 1997). Also, in many of the examples (e.g., signature, throwing, golf swing) provided to explain the principles of the theory, responses that were substantially longer in duration were used, which clearly is long enough for feedback to be used in the control of the movement sequence. Many other examples consistent with schema theory predictions have been found for longer duration movements. Thus, we feel new theories of motor learning and control do not need to be based solely on motor program notions but should incorporate those aspects of schema theory that have been repeatedly substantiated. Specifically, what seems to be important in a new theory is a proposal for a mechanism or processes that produce over practice stable movement structures that do some or all of the following: order, consolidate, or concatenate the movement elements in an abstract proportional manner (e.g., relative timing and relative force). Clearly, movements that last longer than 1 or 2 s maintain their proportional structure even when parameter or effector changes, or both, are required. Recently, Park, Shea, and colleagues (Park & Shea, in press; Park, Wilde, & Shea, 2004; Wilde & Shea, 2004) have demonstrated that participants structure relatively long and complicated movement sequences (8 and 16 elements) by using abstract-proportional principles that allow the movement sequence to be effectively parameterized while maintaining relative amplitudes or relative time, or both. Indeed, those long response sequences can also be effectively transferred to unpracticed effectors. Most interesting, those movement sequences appear to be composed of a number of linked subsequences that form a stable structure for the movement and require more than 3 s to complete. For those reasons, we prefer the term *scalable response structure* (SRS) to the term *generalizable motor program*. We feel the former term reflects not only a cosmetic change aimed at avoiding the motor program controversy but, more important, the finding that short and long duration movement sequences exhibit relatively stable response structures that appear to be represented in an abstract manner. The output from those SRSs clearly exhibit strong tendencies to maintain their relative characteristics when conditions demand changes in amplitude, force, or movement time, alone or in combination. Yet, in the absence of schema theory, there is a profound theoretical void related to the pervasive tendency for a large variety of movements to maintain relative characteristics when circumstances dictate changes in overall force, time, or spatial scale.

Notion of Invariance

The original conceptualization of the GMP as a mechanism that imposes relative structure on movement sequences that are scaled in various ways is supported by the empirical data from a large number of experiments under a variety of conditions. What seems unfortunate is the proposal that the structure is invariant—although that would be a reasonable assumption because the theory was based on motor program concepts. Indeed, the record player analogies that became popular in describing the invariant and variant features of a GMP suggest true invariance. We feel, perhaps borrowing from the dynamical systems literature, that the structure should be viewed as an attractor landscape providing increasing degrees of stability to the relative characteristics of the response with practice, or, borrowing from the sequence learning literature, a processing mechanism that consolidates and concatenates movement elements into an abstract, scaleable movement structure, but not necessarily invariance. That notion must be considered in light of the results of recent experiments that have demonstrated that the relative-timing characteristics become better defined and more stable over practice and that various practice schedule and KR manipulations can differentially enhance that progression. That is, the movement structure is developed over practice and is not simply an innate invariant structure imposed on motor responses. Indeed, it has been found in a number of experiments that participants, when faced with specific goals related to the relative characteristics of the response, begin with a simple structure and over practice adapt it to the specific demands (see Lai et al., 2002, for an example).

Future Directions

In conclusion, we maintain that after almost three decades of research there is a fair amount of support for some of the basic assumptions and predictions of schema theory. In particular, the notion of independent memory states or a processing mechanism responsible for the fundamental movement pattern (GMP) and its parameterization (recall schema), as well as the variability-of-practice hypothesis for parameter learning and effector transfer, which shows the abstract nature of the movement structure, seem to be relatively well supported. It is also clear, however, that some of the ideas proposed in schema theory need to be revised so that the theory can accommodate more recent findings. For example, parameter variability scheduling effects, as well as effects of extended practice, need to be taken into account. Moreover, how the relative movement structure (GMP) or, in our terms, scaleable response structure, and its parameterization are learned should be addressed in a new theory. Those issues are important because the existence of GMPs was simply assumed in the original theory. However, many situations require the learning of a new movement structure (GMP) composed of one or more subsequences that are scalable in one or more dimensions.

With regard to the reliance of schema theory on the motor program, we feel that is not necessary and may even be unnecessarily constraining. Although we do not dispute that prestructured motor sequences (motor programs) are commonly executed, those same learned sequences when "scaled up" in time can be effectively executed under the influence of feedback. Thus, we feel that what has commonly been termed motor programs or preprogrammed responses are simply special cases whereby a stable movement structure is executed relatively uninfluenced by peripheral feedback. This is not a throwback to Adams (1971), because we do not see feedback as playing a guiding or controlling role in skilled movement production; instead, we believe it has a more superficial role in influencing the movement production. Further, that change in frame of reference calls for a change in terms for the movement structure from a GMP to a SRS. The difference in terms reflects the change in conceptualization from a motor program to a response structure while maintaining the relative and abstract nature of the movement plan originally proposed in schema theory. We also argue for a change in emphasis from memory states (schemata) to processing mechanism. The processing mechanism or mechanisms notion suggests a more abstract, generative role in providing a structure to movement sequences than that of memory states. In accordance with the theoretical proposals of Keele et al. (1995) and Verwey (1999, 2000) and the findings of empirical dissociation, one processing mechanism would be responsible for generating the movement structure (SRS) and the other for generating the parametrics of the movement.

Thus, we call for a new motor learning theory that accounts for the stable findings generated, at least in part, as a result of and in response to schema theory. The new theory of control and learning of movement sequences could be built on the foundation that has been laid by schema theory, as just suggested. The challenge is to integrate those recent findings into a new theory that will hopefully provide direction for a new surge in motor learning research, similar to that associated with schema theory more than a quarter of a century ago.

NOTES

1. The criterion for the *citation classic* designation may have changed over the years—we have not been able to confirm that, but there are indications that the article may have achieved citation classic designation as early as 1983. Using today's criterion (400 citations), the article achieved citation classic designation in 1994.

2. Although the recognition schema was an important part of the original conceptualization of schema theory, research related to that aspect of the theory is not reviewed in this article. In the present review, we focus on the recall schema, GMP, and the associated parameterization process.

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