

# Consistent and Variable Practice Conditions: Effects on Relative and Absolute Timing

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**ABSTRACT.** The authors conducted the present experiments to resolve the discrepancy between studies in which relative-timing learning has been found to be enhanced by consistent practice conditions and contextual interference experiments in which relative-timing learning has been found to be enhanced more by random practice than by blocked practice. There were 40 participants in Experiment 1 and 48 in Experiment 2. The results of Experiment 1 extended previous findings: The learning of the relative-timing pattern was systematically enhanced by the degree to which the practice conditions promoted movement consistency (constant > blocked > serial > random). Experiment 2 provided evidence that the discrepancy between the relative-timing effects in the 2 groups of studies was a product of the way in which relative-timing goals and feedback were presented. When the feedback was presented as segment times, random practice resulted in generally more stable relative-timing patterns during acquisition than blocked practice did. Thus, in both experiments, the learning of the relative-timing pattern was enhanced by more stable relative-timing conditions during acquisition. Absolute-timing learning, as indexed by the transfer tests, was enhanced by serial or random practice as compared with constant or blocked practice, and was relatively unaffected by feedback conditions directed at the relative-timing pattern. In terms of motor programming theory, those findings are taken as additional evidence for the disassociation of memories supporting generalized motor program (GMP) performance, as indexed by relative timing, and parameter performance, as indexed by absolute timing.

*Key words:* contextual interference, generalized motor program, motor learning, movement parameters

Schmidt (1975, 1985, 1988) proposed that programmed actions are governed by generalizable motor programs (GMPs) that provide a common structure for a class of movements. Independent rules or schemata provide the scaling characteristics (recall schema) to the GMP so that specific movements can be produced. A postmovement evaluation schema (recognition schema) provides the mechanism for updating the recall schema before the next movement when errors are detected on the previous movement. According to schema theory (Schmidt, 1975; also see Schmidt 1985, 1988; Schmidt & Lee, 1999), a GMP is

developed over practice or experience and becomes the basis for generating movements within a movement class that share the same invariant features (e.g., sequencing, relative timing, and relative force). Specific movements are produced by the premovement assignment of scaling factors, termed *parameters*, such as absolute force or absolute time, via the recall schema. For example, when the time parameter is varied, the invariant features specified by the GMP are thought to remain intact, such that slower movements can be thought of as “stretched-out” (in time) copies of faster movements. Likewise, when the force parameter is manipulated, a movement sequence requiring minimal force can be thought of as a compressed (with respect to force) copy of a more forceful movement.

Although, in his schema theory, Schmidt (1975, 1985, 1988) did not propose specific factors or conditions, other than practice or experience, that should enhance GMP learning, the theory is relatively specific about practice conditions that should enhance the recall schema. Schmidt (1975, 1985; also see Schmidt & Lee, 1999) proposed that the recall schema, which is essentially a rule for parameter specification, is strengthened as a function of variable practice. The recall schema was likened to a regression line determined by the relationship between the parameter values specified to produce the movement and the resultant movement outcome such that with each successive new experience, the relationship is refined (also see Horak, 1992). That notion implies that varied movement requirements should result in a wider range of parameter specification values and associated movement outcomes that, in turn, should enhance the development of the rule for accurately specifying parameters (i.e., the recall schema) in the future. Alternatively, Schmidt suggested that the recall

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schema would not be enhanced by repeated experiences with the same association between a parameter specification and the resultant outcome such as might occur when movement requirements do not often change from trial to trial (i.e., constant practice).

Recently, researchers have devoted a great deal of experimental effort to the study of GMPs and their associated parameters by partitioning movement errors into components attributable to the relative dimensions of the movement, which characterize the GMP, and those attributable to absolute dimensions of the movement, which characterize the parameter or parameters. One prominent line of research targeting GMP and parameter learning involves the contextual interference (CI) manipulation (e.g., Sekiya, Magill, & Anderson, 1996; Sekiya, Magill, Sidaway, & Anderson, 1994; Wulf, 1992b; Wulf & Lee, 1993). A low level of contextual interference is thought to be created during blocked practice in which a single task variation is practiced before additional practice is given on other task variations. In contrast, one can create high contextual interference by using serial (Sekiya et al., 1996; Sekiya et al., 1994) or random (e.g., Wulf, 1992b; Wulf & Lee, 1993) practice schedules in which task variations change from trial to trial in either a predictable (serial) or nonpredictable (random) manner. Serial and random practice are thought to invoke similar levels of CI (see Lee & Magill, 1983). However, studies in which serial and random practice have been used have yielded conflicting results with respect to GMP and parameter learning. Sekiya and colleagues (Sekiya et al., 1996; Sekiya et al., 1994), for example, found that GMP learning was not enhanced by practice under serial practice as compared with practice under blocked practice. Those researchers did find typical CI effects for parameter errors: Compared with blocked practice conditions, serial practice resulted in larger parameter errors during acquisition and smaller parameter errors on retention tests. The findings of Sekiya and colleagues, that serial practice leads to enhanced parameter learning, are consistent with the majority of more traditional CI experiments (e.g., Lee & Magill, 1983; Shea & Morgan, 1979). In those experiments, performance was not partitioned into GMP and parameter error, but a single error measurement (e.g., movement time or timing error) that reflected parameter errors was used. Contrary to the findings of Sekiya and colleagues, Wulf and colleagues (e.g., Wulf, 1992b; Wulf & Lee, 1993) demonstrated enhanced GMP learning in random practice as compared with the learning achieved in blocked practice, with no differences noted between practice conditions for parameter learning.

The discrepancies in the findings of Sekiya (Sekiya et al., 1996; Sekiya et al., 1994) and Wulf (e.g., Wulf, 1992b; Wulf & Lee, 1993) are particularly troublesome for two reasons. First, apparently similar variable practice conditions (i.e., serial and random practice)—which should, from a CI perspective, produce similar levels of interference and which were shown by Lee and Magill, 1983, to produce similar CI effects when a single error measure was used—

produced diametrically opposing effects when a specific relative-timing structure was imposed on the task and GMP and parameter learning were assessed. That is, compared with blocked practice, serial practice has been shown by Sekiya and colleagues to result in enhanced parameter learning with little or no effect on GMP learning. Random practice, on the other hand, has been shown by Wulf and colleagues to lead to enhanced GMP learning, with no effect on parameter learning, as compared with the effects of blocked practice. Second, the findings of Wulf and colleagues are not consistent with the proposal of Lai and colleagues (Lai & Shea, 1998, 1999; Lai, Shea, Wulf, & Wright, 2000). Their proposal was developed as a result of a series of experiments in which constant and random practice were contrasted under various knowledge of results (KR) conditions. In the proposal, it is argued that practice conditions that promote movement consistency during acquisition lead to better GMP learning than practice conditions that produce movement variability.

In an attempt to address those discrepancies and determine underlying conditions that promote relative- and absolute-timing learning, we tested four practice conditions in Experiment 1. Each of the practice conditions has been paired in earlier experiments in which relative- and absolute-timing errors were measured, but they have not been investigated under common conditions in a single experiment. Specifically, our purpose in Experiment 1 was to determine the effects of constant, blocked, serial, and random practice schedules on relative-timing (a measure of GMP development) and absolute-timing (a measure of parameter selection) errors. Contrary to the findings of Wulf (1992b; Wulf & Lee, 1999) we expected to find systematic increases in relative-timing learning as the consistency and predictability of the practice environment was increased. Further, we predicted that absolute-timing learning would be enhanced by the variability and unpredictability of the practice environment. Those predictions were based on the findings of Lai and colleagues (e.g., Lai & Shea, 1998, 1999; Lai et al., 2000) reported in the KR literature and on the parameter findings of Sekiya and colleagues (Sekiya et al., 1996; Sekiya et al., 1994) in the CI literature. We designed Experiment 2 to specifically consider one potential explanation for the findings of Wulf and colleagues regarding the role of random practice and relative-timing learning. We focused in that experiment on the potential effects of presenting segment goals and feedback in terms of either segment ratios (Lai et al., 2000; Sekiya et al., 1996; Sekiya et al., 1994) or segment movement times (Wulf, Lee, & Schmidt, 1994). The way in which the movement goal and feedback are presented to the learner may affect relative- and absolute-timing learning either by causing the performers to focus more (or less) on the relative or absolute characteristics of the task or by increasing or decreasing the processing demands associated with the feedback. Our overall objective in this article is to begin the process of determining the underlying factors that influence

relative- and absolute-timing learning so that unified predictions and explanations can be applied across paradigms.

### EXPERIMENT 1

In Experiment 1, constant, blocked, serial, and random practice schedules were manipulated with respect to absolute time, whereas the relative-timing structure of all tasks was held constant. Based on previous findings (Lai & Shea, 1998, 1999; Lai, Shea, & Little, in press), we predicted that relative-timing errors would decrease as movement consistency created by the practice schedule during acquisition increased. Thus, we predicted that relative-timing errors (a measure of the GMP) would be smaller for constant and for blocked practice, which should promote movement consistency, than for serial and for random practice, which should promote relatively high movement variability. In contrast, for absolute-timing error (a measure of parameter selection), we predicted that constant and blocked practice would result in poorer transfer performance than serial and random practice (see Lai & Shea, 1998, for measures of movement variability in constant vs. serial practice). Those predictions were based on the notion that constant and blocked practice result in relatively stable learning environments because parameter requirements generally do not change from trial to trial in those practice conditions. Alternatively, random and serial practice create less stable learning environments because the parameter requirements change from trial to trial in those practice conditions.

Testing those manipulations in a single experiment is important for two theoretical reasons. First, it is important to determine the extent to which relative- and absolute-timing learning are systematically affected by movement consistency created by the practice schedule. Lai and Shea (1998) have proposed that increased movement consistency leads to enhanced relative-timing learning and degraded absolute-timing learning. Alternately, they proposed, increased movement variability would degrade relative-timing learning and enhance absolute-timing learning. Second, findings of systematic effects should afford us the opportunity to apply unified explanations for relative- and absolute-timing learning effects across manipulations and paradigms (e.g., CI and KR), which have traditionally been dealt with as independent phenomena.

### Method

#### Participants

Forty undergraduate students participated in this experiment for partial course credit. Participants had no prior experience with the experimental task and were not aware of our specific purposes in the study. Each participant was requested to read and sign an informed consent form before taking part in the experiment.

#### Apparatus

A computer, color monitor, and keyboard were placed on a standard table. Participants were asked to sit on a chair,

face the computer monitor, and adjust the position of the keyboard so that they could comfortably use the numeric key pad with their right hand. All movements were made on the numeric keypad portion of the keyboard.

#### Task

The participants were asked to sequentially depress four keys (2, 4, 8, and 6) on the numeric key pad portion of the keyboard with the index finger of their right hand. At the beginning of each trial, the relative goal ratio for each movement segment (with segments being defined by two consecutive key presses) and the total goal movement time (GMT) were presented on the computer monitor. The relative goal segment ratios of all tasks were 22.2%, 44.4%, and 33.3% for Segments 1 through 3, respectively. The GMTs were 700 ms (Task A), 900 ms (Task B), and 1,100 ms (Task C) for variable practice groups (blocked, serial, and random schedules). The GMT was 900 ms for the constant practice group. The actual goal segment times in milliseconds are provided in Table 1.

Before beginning the acquisition phase of the experiment, the participants were given detailed instructions on what the goal segment ratios and GMT meant and how to interpret the feedback that was to be provided. The participants were asked to be as accurate as possible with regard to both the relative goal segment ratios and the GMT. After completing the movement sequence, actual segment ratios were displayed directly under the goal segment ratios and the actual total movement time (MT) was displayed directly under the GMT. If a participant depressed the keys in an incorrect fashion, the correct sequence was displayed and the trial was repeated.

#### Procedure

Participants were randomly assigned to one of four acquisition practice conditions (constant, blocked, serial, or random). The constant practice group experienced only Task B (GMT of 900 ms) during acquisition. In each of the three variable practice conditions, Tasks A, B, and C made up 33% of the acquisition trials. In the blocked practice condition, all trials with one task were completed before introducing the next task variation. In the serial practice conditions, the order in which the tasks were presented was

**TABLE 1**  
Goal Segment Times (ms) for the Tasks Used  
in Experiment 1

Task	Segment ratio			Total
	1 (22.2%)	2 (44.4%)	3 (33.3%)	
A	156	311	233	700
B	200	400	300	900
C	244	489	367	1,100
D	289	578	433	1,300

repeated throughout acquisition. In both the blocked and serial practice conditions, the order in which the tasks were presented was either ABC, CAB, or BCA. In the random practice condition, the task variations were presented in random order, with the restriction that each variation be presented an equal number of times.

Before each trial, the letter (A, B, or C) indicating the task variation, as well as the goal segment ratios and GMT, appeared on the screen for 4 s (e.g., B 22.2 – 44.4 – 33.3 900). The participants were asked to start their movements within 4 s after that information was displayed. If they failed to do so, a message appeared on the screen indicating that they had taken too long and the trial would be repeated. After the key sequence was completed, the segment ratios and total MT were displayed under the respective goal segment ratios and GMT.

The participants were informed that the experiment consisted of three phases, acquisition, retention, and transfer, and that the retention and transfer phases would be conducted on the following day. All participants performed 108 trials (9 blocks of 12 trials) during the acquisition phase. The no-KR retention and transfer tests were administered approximately 24 hr after the completion of the acquisition phase. The time between the retention and transfer phases was 5 min, with retention tested before transfer. In the retention test, all participants performed one 12-trial block on Task B (900 ms). In the transfer test, participants performed 12 trials on a novel task variation (Task D) that had a longer GMT (1,300 ms) but the same goal relative timing (22.2%, 44.4%, 33.3%) as tasks performed during acquisition and retention.

**Measurement**

The dependent variables of interest were relative-timing error (*AE prop*), relative-timing variability (*VE*), and absolute-timing error (*E*). We used relative-timing error as a measure of the proficiency of the GMP, relative-timing variability as a measure of the consistency of relative-timing performance, and absolute-timing error as a measure of the proficiency of parameterization.

Relative-timing error (*AE prop*) was computed as the sum of the absolute differences between the goal proportions and the actual proportions for each segment. That measure provides an estimate of the accuracy of relative-timing performance. In equation form,

$$AE\ prop = |R_1 - 22.2| + |R_2 - 44.4| + |R_3 - 33.4|$$

where  $R_n = (\text{actual MT of Segment}_n / \text{total MT}) \times 100$ . Thus,  $R_1$ ,  $R_2$ , and  $R_3$  are the proportions of total movement time used, respectively, in Segments 1, 2, and 3.

The consistency of relative-timing performance (*VE*) was determined as the standard deviation of the relative-timing errors for a block of trials. *VE* is a measure of variability and is computed as the standard deviation of the signed errors.

For absolute-timing performance, we used *E* (total error) to characterize parameter errors, because *E* can be thought

of as a measure of overall parameter accuracy in which both parameter biases and variability are considered. Thus, absolute-timing error (*E*) was computed as  $(CE^2 + VE^2)^{1/2}$ , where *CE* is a measure of bias and is computed as the average of the signed errors (*GMT* – *MT*).

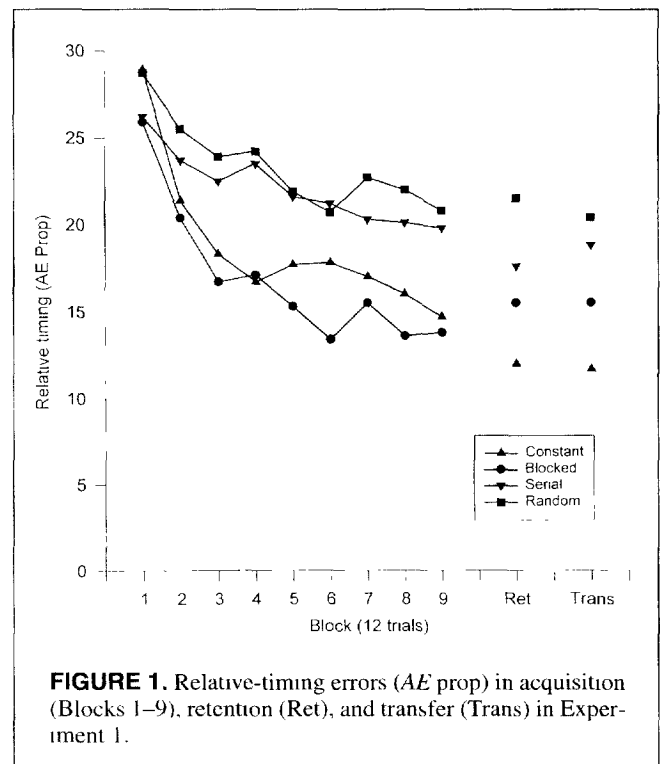
**Results**

To analyze acquisition performance, we evaluated relative-timing (*AE prop*), relative-timing (*VE*), and absolute-timing (*E*) errors in 4 (practice condition: constant, blocked, serial, and random) × 9 (block: 1–9) analyses of variance (ANOVAs) with repeated measures on block. Retention and transfer performances were evaluated in separate 4 (practice condition: constant, blocked, serial, and random) ANOVAs. Relative-timing *AE prop*, relative-timing *VE*, and absolute-timing *E* are displayed by block and practice condition in Figures 1–3, respectively.

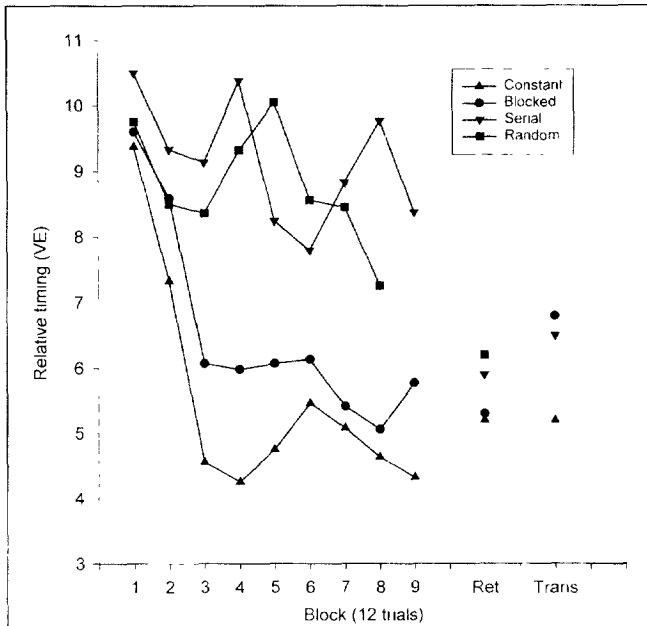
**Relative-Timing Error (*AE prop*)**

*Acquisition*

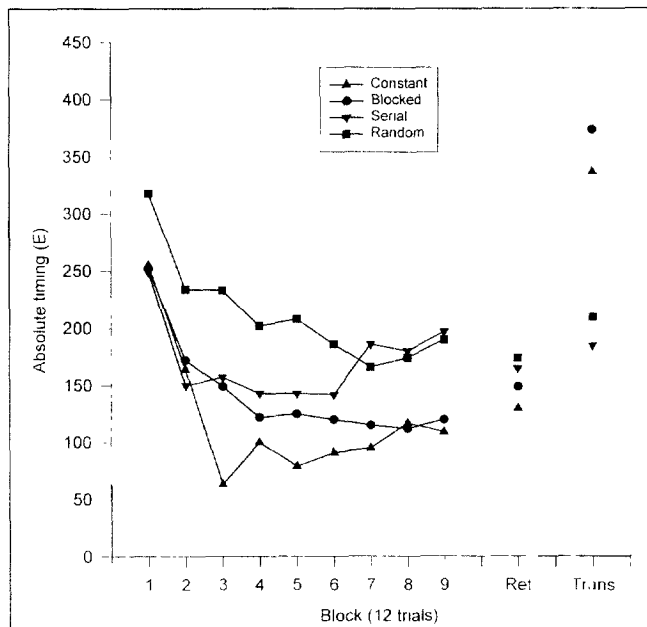
All groups improved their relative-timing accuracy (*AE prop*) from the beginning to the end of practice; the constant and the blocked groups exhibited smaller relative-timing errors than the serial and the variable practice groups. The analysis indicated main effects of practice condition,  $F(3, 36) = 3.41, p < .05$ , and block,  $F(8, 281) = 27.21, p < .01$ . Duncan's new multiple range test on practice condition indicated that relative-timing errors were smaller for the blocked group than for the serial and the random groups. In addition, the relative-timing errors for the constant practice



**FIGURE 1.** Relative-timing errors (*AE prop*) in acquisition (Blocks 1–9), retention (Ret), and transfer (Trans) in Experiment 1.



**FIGURE 2.** Relative-timing errors (*VE*) in acquisition (Blocks 1–9), retention (Ret), and transfer (Trans) in Experiment 1.



**FIGURE 3.** Absolute-timing errors (*E*) in acquisition (Blocks 1–9), retention (Ret), and transfer (Trans) in Experiment 1.

group were not different from those of the blocked group. The multiple range test on block indicated that relative-timing errors were larger on Block 1 than on Block 2 and were smaller on Blocks 8 and 9 than on all other blocks.

The Practice Condition  $\times$  Block interaction,  $F(24, 281) = 2.47, p = .05$ , was also significant. Simple main effects

analysis indicated that relative-timing errors were similar for all groups on Blocks 1 and 2, but the serial and the random groups produced larger relative-timing errors on Blocks 3 through 9 than the blocked and constant groups did. In addition, on Block 6 relative-timing errors were smaller for the constant practice group than for all other groups.

*Retention*

Relative-timing errors generally increased in the following order: constant < blocked < serial < random practice. The analysis indicated a main effect of practice condition,  $F(3, 36) = 5.04, p < .01$ . Duncan's new multiple range test indicated that relative-timing errors were smaller for the constant ( $M = 12.7, SE_M = 1.13$ )<sup>1</sup> and the blocked practice groups ( $M = 15.5, SE_M = 2.13$ ) as compared with the random practice group ( $M = 21.5, SE_M = 1.21$ ). Relative-timing error for the serial practice group ( $M = 17.6, SE_M = 1.89$ ) was not different from that of either the blocked or the random practice group but was higher than that of the constant practice group.

*Transfer*

The pattern of results from retention to transfer was generally similar. The analysis indicated a main effect of practice condition,  $F(3, 36) = 6.47, p < .01$ . Duncan's new multiple range test indicated that relative-timing errors were smaller for the constant ( $M = 11.7, SE_M = 0.66$ ) and the blocked ( $M = 15.5, SE_M = 1.06$ ) practice groups than for the random ( $M = 20.5, SE_M = 2.06$ ) practice group. Relative-timing error for the serial practice group ( $M = 18.8, SE_M = 1.72$ ) was not different from that of either the blocked or the random practice group but were higher than that of the constant practice group.

**Relative Timing (*VE*)**

*Acquisition*

The relative-timing pattern of all groups became more consistent over practice; however, the improvements in consistency were much more substantial early in practice for the constant and the blocked practice groups than for the serial and the random practice groups. The analysis indicated main effects of block,  $F(8, 281) = 8.48, p < .01$ , and practice condition,  $F(3, 36) = 11.92, p < .01$ . The analysis also indicated a Practice Condition  $\times$  Block interaction,  $F(24, 281) = 1.87, p < .01$ . Simple main effects analysis indicated that the relative-timing patterns were more consistent for the constant and the blocked practice conditions on Blocks 3–9 than for the serial or the random practice condition. Although some isolated differences were detected between the serial and the random practice groups and between the constant and the blocked practice groups, those groups were generally not different from each other.

*Retention*

The main effect of practice condition was not significant,  $F(3, 36) < 1, p > .05$ .

### Transfer

The main effect of practice condition was not significant,  $F(3, 36) = 2.67, p > .05$ .

### Absolute-Timing Error (*E*)

#### Acquisition

There was substantial reduction in absolute-timing error (*E*) early in acquisition, with little additional improvement across the later acquisition blocks. The analysis indicated main effects of practice condition,  $F(3, 36) = 4.71, p < .01$ , and block,  $F(8, 281) = 15.49, p < .01$ . Duncan's new multiple range test on practice condition indicated that absolute-timing errors were smaller for the constant and the blocked groups than for the random group. The absolute-timing performance of the serial practice group was not different from that of either the random or the blocked group. The multiple range test on block indicated absolute-timing errors were higher in Block 1 than in all subsequent blocks. In addition, absolute-timing errors were lower in Blocks 5–7 than in Blocks 1–3. The Practice Condition  $\times$  Block interaction,  $F(24, 281) = 1.10, p > .05$ , was not significant.

#### Retention

The analysis failed to detect a main effect of practice condition.

#### Transfer

The analysis indicated a main effect of practice condition,  $F(3, 36) = 6.30, p < .01$ . Duncan's new multiple range test indicated that absolute-timing errors were smaller for the serial ( $M = 185, SE_M = 24$ ) and the random ( $M = 194, SE_M = 28$ ) practice groups than for the constant ( $M = 337, SE_M = 48$ ) and the blocked ( $M = 374, SE_M = 46$ ) practice groups.

## Discussion

During acquisition, relative-timing performance improved more rapidly for the constant and the blocked practice groups than for the serial and the random practice groups. By Block 3 of acquisition, the relative-timing performance of the constant and the blocked groups was clearly superior to those of the serial and the random practice groups. On the retention and transfer tests, the groups were ordered in terms of relative timing from smaller to larger, as follows: constant, blocked, serial, and random. However, a pattern similar to that observed toward the end of acquisition was detected by the retention and transfer analyses. That is, the constant and the blocked groups produced smaller relative-timing errors than the random practice group, whereas the serial practice group was intermediate between the blocked and the random practice conditions.

The present relative-timing errors (*AE* prop) and variability (*VE*) results were also consistent with the previous findings of Lai and colleagues (Lai & Shea, 1998; Lai et al., in press), who compared constant and serial practice. Furthermore, the present data were consistent with the notion that

factors that increase movement consistency during acquisition also enhance GMP learning. With respect to the CI effect, the present results were consistent with those of Sekiya and colleagues (Sekiya et al., 1996; Sekiya et al., 1994), who contrasted blocked and serial practice. As in the present experiment, Sekiya et al. (1996; Sekiya et al., 1994) found no differences in relative-timing errors between blocked and serial practice. The present results, however, were directly contrary to those of Wulf and Lee (1993), who found that random practice resulted in smaller relative-timing errors than blocked practice did.

A somewhat similar picture emerged for absolute-timing errors during acquisition. Similar to relative timing, constant and blocked practice generally resulted in smaller absolute-timing errors than did random practice, and serial practice resulted in errors that were not significantly different from those of either the blocked or the random practice conditions. A quite different picture was found, however, when absolute-timing errors in transfer were considered. Although no significant differences between practice conditions were observed on the retention test, absolute-timing errors during transfer were considerably larger for the constant and the blocked groups than for the serial and the random groups.

The present absolute-timing results, as was the case for relative timing, were consistent with the results of Lai and colleagues (Lai & Shea, 1998; Lai et al., in press), who compared constant and serial practice. The transfer results were also generally consistent with the retention findings of Sekiya et al. (1996; Sekiya et al., 1994). Sekiya and colleagues found advantages of serial practice over blocked practice on a delayed retention test, whereas we found relatively large differences on a delayed transfer test. The present absolute-timing effects were also consistent with the typical CI effects: Compared with blocked practice, random practice resulted in inferior acquisition performance, but superior learning, as indexed by transfer performance. The finding that the random practice participants learned to more effectively scale movements than the blocked practice participants is especially relevant if one considers that in many of the traditional CI experiments (see Magill & Hall, 1990, for a review of the CI effect) error measures that reflect parameter errors were used<sup>2</sup> (e.g., movement time and timing error). For example, Shea and Morgan (1979), who first demonstrated the CI effect in motor skills, used movement time as a primary dependent measure. Movement time is clearly a measure of absolute time. Similarly, Lee and Magill (1983, Experiments 1 and 2) used movement time (also see Gabriele, Hall, & Buckolz, 1987; Limons & Shea, 1988; Shea & Zimny, 1988) and absolute constant error (Experiment 3; also see Carnahan, Van Eerd, & Allard, 1990; Gabriele, Hall, & Lee, 1989; Gabriele, Lee, & Hall, 1991) as dependent variables; both are measures of absolute time that are not sensitive to changes in movement structure (i.e., relative time-GMP).

In summary, the results of Experiment 1 were consistent

with the notion that response consistency from trial to trial in acquisition leads to enhanced GMP learning. However, parameter specification is enhanced, particularly during transfer, by task variations that are scheduled so that the parameter requirements change from trial to trial. That tradeoff, in which one set of practice conditions benefits GMP learning to the detriment of parameter learning and another set of practice conditions benefits parameter learning to the detriment of GMP learning, should provide the impetus for researchers to develop new practice schedules aimed at enhancing both relative- and absolute-timing learning (for an example, see Lai et al., 2000). These findings also add to a growing number of examples of the independence of GMP and parameter learning and suggest at least one factor, movement consistency, that seems to affect GMP learning across paradigms.

## EXPERIMENT 2

As was noted in the discussion of Experiment 1, there remains a discrepancy between the results from Experiment 1 (also see Lai & Shea, 1998; Lai et al., in press; Sekiya et al., 1996; Sekiya et al., 1994) and those of Wulf and colleagues (Wulf, 1992b; Wulf & Lee, 1993) regarding the role of blocked and random practice in relative-timing learning. In Experiment 1, blocked practice was found to be more beneficial than random practice for relative-timing performance and learning. In contrast, Wulf and colleagues have argued that random practice exerts its beneficial effect at the level of the GMP (relative timing). One important question, then, is what factor or factors might account for the discrepant findings.

One difference between the present sets of experiments and that of Wulf and Lee (1993) was the method by which the relative-timing goals and feedback were presented to the learners. In Experiment 1, as in earlier experiments by Lai and Shea (1998; Lai et al., 2000) and a few of the experiments by Wulf and colleagues (e.g., Wulf et al., 1994), the segment goals were expressed as ratios of the total time (e.g., 22.2%, 44.4%, 33.3%), and the feedback provided was in the same form (i.e., segment ratios). In contrast, Wulf and Lee (1993) presented segment goals in terms of absolute segment times (e.g., 200 ms, 400 ms, 300 ms), even though those numbers represented the same ratios (22.2%, 44.4%, 33.3%) as in the experiments of Lai and colleagues. The feedback provided after each trial was also expressed as segment times. That procedural difference may have had an impact on the results. For example, the way in which the goals are presented and feedback is provided may differentially affect the degree to which the learner's attention is drawn to the relative or absolute characteristics of the task, which in turn might change the effects of random and blocked practice schedules on relative and absolute timing. In addition, the processing required to effectively translate the two forms of goals and the feedback may interfere with other processing requirements in one practice condition but not in another. Therefore, our specific purpose in Experi-

ment 2 was to contrast ratio and segment time goals and feedback in blocked and random practice. If that factor critically affects relative-timing performance, we should be able to shed some light on why discrepancies occurred across experiments and provide additional insight into the boundary conditions under which the CI effect operates.

## Method

### *Participants*

Forty-eight undergraduate students participated in this experiment for partial course credit. Participants had no prior experience with the experimental task and were not aware of our specific purposes in the study. Each participant was requested to read and sign an informed consent form before participating in the experiment.

### *Apparatus*

The apparatus was identical to that used in Experiment 1.

### *Task*

The participants were asked to sequentially depress with the index finger of their right hand four keys (2, 4, 8, and 6) on the numeric pad portion of the computer keyboard. Before each trial, the segment goals and total goal movement time (GMT) were presented on the computer monitor. The relative goal segment ratios for all tasks were 22.2%, 44.4%, and 33.3%. The segment goals were presented as either goal segment ratios (e.g., 22.2%, 44.4%, or 33.3%) or as goal segment times (e.g., 200 ms, 400 ms, and 300 ms, for a 900-ms GMT). The participants were asked to be as accurate as possible with regard to the segment goals and GMT. Upon the completion of the trial, actual segment performances were displayed (in the same format as they were presented—ratios or movement time) directly under the segment goals, and total movement time for the trial was displayed directly under the GMT. If a participant depressed the keys in an incorrect fashion, the correct sequence was displayed and the trial was repeated.

### *Procedure*

Participants were randomly assigned to one of four acquisition conditions in a 2 (practice condition: blocked or random)  $\times$  2 (segment feedback: ratio or segment time) arrangement. Blocked and random practice conditions were identical to those used in Experiment 1. In addition, the ratio feedback was identical to that used in Experiment 1. We created the segment time feedback condition by providing segment goals and segment feedback in milliseconds rather than by expressing them as a ratio. The latter feedback condition was similar to that used by Wulf and Lee (1993). All other procedures were identical to those of Experiment 1.

### *Measurement*

Relative timing (*AE prop*), relative timing (*VE*), and absolute-timing errors were identical to those used in Experiment 1.

**Results**

To analyze acquisition performance, we evaluated relative timing (*AE prop*), relative timing (*VE*), and absolute-timing (*E*) errors in 2 (practice condition: blocked vs. random) × 2 (feedback: ratio vs. absolute time) × 9 (block) analyses of variance (ANOVA) with repeated measures on block. Retention and transfer performance was evaluated in separate 2 (practice condition: blocked vs. random) × 2 (feedback: ratio vs. absolute time) ANOVAs. Relative timing (*AE prop*), relative timing (*VE*), and absolute timing (*E*) are displayed by block for practice conditions and feedback conditions in Figures 4–6, respectively.

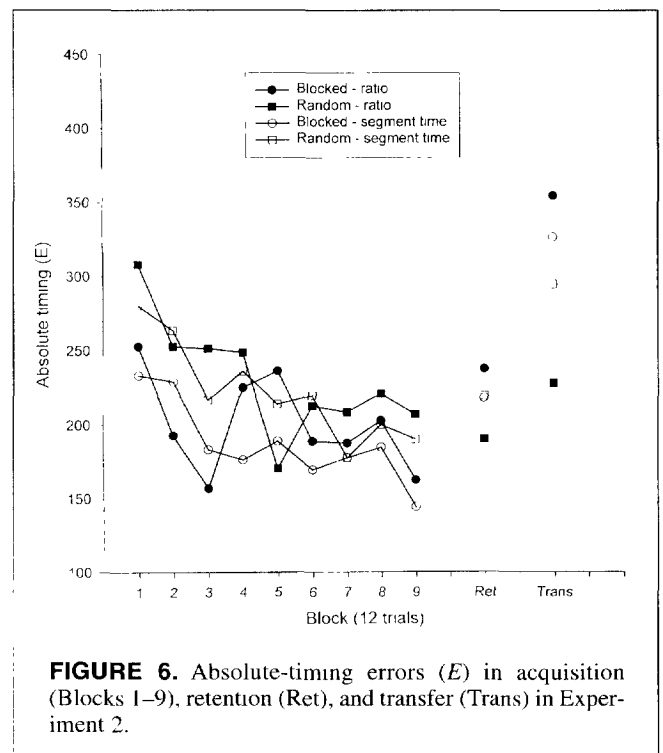
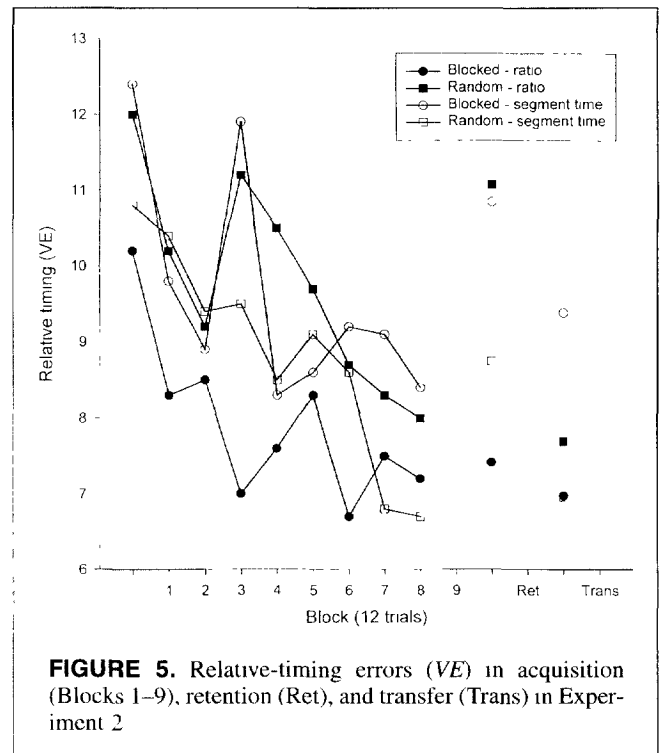
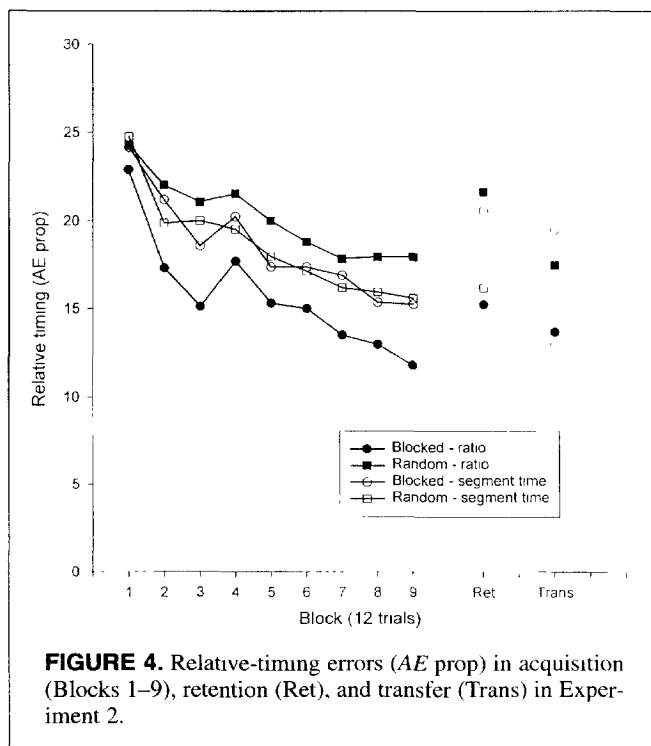
**Relative Timing (*AE prop*)**

*Acquisition*

All groups improved their relative-timing (*AE prop*) performance from the beginning to the end of acquisition; the relative-timing performance of the blocked practice conditions ( $M = 18.9, SE_M = 0.59$ ) tended to have smaller relative-timing errors than the random practice conditions ( $M = 22.1, SE_M = 0.55$ ). However, the analysis indicated only a main effect of block  $F(8, 352) = 21.13, p < .01$ . Duncan's new multiple range test on block indicated that relative-timing errors were larger on Block 1 than on all subsequent blocks. In addition, relative-timing errors were larger on Blocks 2–4 than on Blocks 5–9.

*Retention*

The analysis indicated only a Practice Condition × Feedback interaction,  $F(1, 44) = 11.31, p < .01$ . Simple main effect analysis indicated that for the ratio-feedback condi-



tion, blocked practice ( $M = 15.3, SE_M = 0.86$ ) resulted in smaller relative-timing errors than random practice ( $M = 21.6, SE_M = 1.07$ ). When segment times were provided as feedback, however, random practice ( $M = 16.2, SE_M = 1.54$ ) resulted in smaller relative-timing errors than did blocked practice ( $M = 20.5, SE_M = 2.35$ ).

### Transfer

The pattern of results from delayed retention to delayed transfer was generally similar. The analysis indicated only a Practice Condition  $\times$  Feedback interaction,  $F(1, 44) = 10.71, p < .01$ . Simple main effect analysis indicated that for the ratio-feedback conditions, blocked practice ( $M = 13.7, SE_M = 0.83$ ) resulted in smaller relative-timing errors than did random practice ( $M = 16.4, SE_M = 1.36$ ). When segment times were provided as feedback, however, random practice ( $M = 12.8, SE_M = 1.36$ ) resulted in smaller relative-timing errors than blocked practice did ( $M = 19.5, SE_M = 1.86$ ).

### Relative Timing (VE)

#### Acquisition

The relative-timing pattern of all groups became more consistent over practice; however, the improvements in segment consistency were more substantial for the blocked-ratio group than for the random-ratio group. Although the random-segment time group was more consistent by the end of practice, there did not appear to be a consistent difference between the stability of the blocked-segment time group and the random-segment time group. The analysis indicated a main effect of block,  $F(8, 352) = 5.32, p < .01$ . The analysis failed to detect a main effect of either practice condition,  $F(1, 44) = 1.30, p > .05$ , or feedback,  $F(1, 44) = 1.30, p > .05$ . The analysis did detect a Practice Condition  $\times$  Feedback interaction, however,  $F(1, 44) = 4.20, p < .05$ . Simple main effects analysis indicated that the relative-timing pattern was more consistent for the blocked-ratio condition than for the random-ratio condition. However, the relative-timing performance of the random-segment time group, which progressively became less variable over practice, was more stable than that of the blocked-segment time group on Block 4 and on Blocks 8 and 9. The segment variability of the blocked-segment time group tended not to improve as consistently as that of the random-segment time group and was particularly unstable on the block immediately after the first change in task requirements (Block 4).

#### Retention

No main effects of practice condition,  $F(1, 44) < 1, p > .05$ , or feedback,  $F(1, 44) < 1, p > .05$ , were detected in the analysis. However, the Practice Condition  $\times$  Feedback interaction was significant,  $F(1, 44) = 6.75, p < .05$ . Simple main effects analysis indicated more consistent relative-timing performance for the blocked-ratio ( $M = 7.42, SE_M = 0.83$ ) and the random-segment time ( $M = 8.75, SE_M = 1.25$ ) groups than for the random-ratio ( $M = 11.08, SE_M = 1.27$ ) and block-segment time ( $M = 10.85, SE_M = 1.01$ ) groups.

#### Transfer

Main effects of practice condition,  $F(1, 44) < 1, p > .05$ , or feedback,  $F(1, 44) < 1, p > .05$ , were not found. The

Practice Condition  $\times$  Feedback interaction was also not significant,  $F(1, 44) = 2.84, p > .05$ .

### Absolute-Timing Error (E)

#### Acquisition

The analysis indicated main effects of practice condition,  $F(1, 44) = 5.52, p < .01$ , and block,  $F(8, 352) = 8.95, p < .01$ . The absolute-timing errors were smaller for the blocked groups ( $M = 187, SE_M = 9$ ) than for the random groups ( $M = 226, SE_M = 7$ ). Duncan's new multiple range test on block indicated that absolute-timing errors were higher in Block 1 than in all subsequent blocks. In addition, relative-timing errors were larger on Block 2 than on Blocks 4–9.

#### Retention

No significant main effects or interactions were detected.

#### Transfer

The analysis indicated a main effect of practice condition,  $F(1, 44) = 15.37, p < .01$ , with absolute-timing errors smaller for the random practice groups ( $M = 233, SE_M = 14$ ) than for the blocked practice groups ( $M = 353, SE_M = 32$ ).

## Discussion

The blocked and the random practice groups that received segment ratio goals and segment ratio feedback replicated very closely the results of the corresponding groups in Experiment 1. The data were also consistent with earlier studies of the learning effects of constant and serial practice (e.g., Lai & Shea, 1998; Lai et al., in press). Blocked practice generally resulted in smaller relative-timing errors in retention and transfer than did random practice. However, the blocked and the random practice groups that received segment time goals and segment time feedback produced a quite different relative-timing error profile. Under segment time goals and segment time feedback conditions, random practice resulted in generally smaller relative-timing errors in retention and in transfer than blocked practice did. That finding replicates the results of Wulf and colleagues (e.g., Wulf, 1992b; Wulf & Lee, 1993). Simply changing the form in which the segment time goals and feedback were presented reversed the pattern of relative-timing errors that emerged. Thus, the nature of the goals and the feedback concerning the relative-timing dimension of the movement appears to be an important factor in mediating the impact of random and blocked practice on relative-timing (GMP) learning.

The important question is, Why do the type of goal and the feedback have such a large effect on relative-timing learning in blocked and random practice? It is interesting that the relative-timing pattern for the random-segment time group was not only more accurate than that of the blocked-segment time group during retention and transfer, random practice with segment time information also tended to result in less variable relative-timing patterns during

acquisition. The variability of the relative-timing pattern for the random–segment time group decreased steadily across practice, whereas the transitions from the first to the second task variation for the blocked–segment time group resulted in relatively large increases in segment variability. By the end of practice the relative-timing pattern of the random–segment time group was clearly less variable than that of the blocked–segment time group. That finding is consistent with our hypothesis that factors that decrease response variability during acquisition result in enhanced relative-timing development.

We are still left with the question as to why ratio and segment time goals and feedback differentially produce conditions conducive to relative-timing (GMP) learning. One possibility is that when ratio segment goals and feedback information were presented in a random practice condition (that is, when the absolute timing was changing from trial to trial) and the performers' attention was directed to the common timing structure across tasks, that information was somewhat confusing and overly demanding. Although the segment goal ratios were the same from trial to trial, the segmental movements had to be lengthened or shortened in response to changes in the overall duration (absolute time) of the movement. The feedback then represented the relative proportion of time spent traversing the various segments as a function of the actual overall duration. Thus, to perform the same segment ratio goals, the participant had to produce different segmental movement times for the different task variations. Similarly, the same error score on two subsequent trials could have reflected different segment movement times. That error message may have been overly demanding for the random practice participants because they then had to translate that information into a more meaningful form that they could use to enhance subsequent experiences with that task variation and with performance in general. The additional processing was added to the already high cognitive loads generally thought to be imposed by random practice conditions. The added processing load may either have disrupted the reconstruction of the action plan for the next movement (e.g., Lee & Magill, 1983, 1985) or interfered with the inter-item processing that has been proposed to enhance random practice (e.g., Shea & Zimny, 1983, 1988), or both. The suggestion that supplemental processing loads imposed by the goal and the feedback conditions can be disruptive in random practice but not in blocked practice is not new. Wright, Li, and Whitacre (1992) have shown that asking participants to engage in additional inter-item processing during acquisition resulted in a detriment in the acquisition and retention performance of random practice groups. However, the additional processing was beneficial for blocked practice conditions, presumably because it explicitly revealed the relationship between tasks (i.e., relative-timing pattern). That information may have caused an increase in the inter-item processing for the blocked group that benefited relative-timing learning.

When goals and feedback were presented as segment

times, the blocked practice group had significant difficulty, as indicated by substantial increases in relative-timing variability when they transferred from one task variation to another. That difficulty may indicate that segment time goals and feedback provided in blocked conditions do little to reveal the underlying structure of the task variations. Clearly, in blocked practice, segment time goals and feedback do little to point the performers' attention to the common structural features of the tasks. In the random practice conditions with segment time goals and feedback, however, the common structure of the movement should be effectively revealed, implicitly if not explicitly, through practice, because the participants' attention is directed to the common structure of the movement sequence as the parameters are varied from trial to trial.

Absolute-timing performance in the present experiment, as in the earlier experiments of Lai and colleagues (Lai, 1998, 1999; Lai et al., in press), seemed to be relatively unaffected by manipulations directed at the relative-timing component of the task (also see Wright & Shea, in press). More specifically, the way in which the segment goals and feedback were provided did not appear to substantially affect parameter learning. As in previous experiments, absolute-timing errors in transfer tended to be smaller for the random practice conditions than for the blocked practice conditions although the differences between practice conditions for the segment time feedback groups appeared to be somewhat smaller than those for the ratio feedback groups. The finding of relatively small differences in absolute-timing errors in the segment time goal and feedback condition is consistent with the results of Wulf and colleagues (Wulf, 1992b; Wulf, Schmidt, & Deubel, 1993). In fact, those authors have suggested that the CI effect occurs at the level of the GMP and not at the level of the parameters because they failed to find random and blocked practice differences on the parameter (absolute timing) significant even though the sample data favored the random practice groups. The present data, however, clearly demonstrate that relative-timing learning, but not absolute-timing learning, is affected by the way the segment goals and feedback are presented during acquisition.

## GENERAL DISCUSSION

Our primary purpose in this article is to extend previous research on relative- and absolute-timing learning, in which constant and serial practice were used in the investigation of specificity–variability and KR (i.e., reduced frequency and bandwidth) issues, to other methods of scheduling variability (i.e., blocked and random practice) in the CI literature. That issue is important empirically if we are to reconcile the findings of Lai and colleagues (Lai & Shea, 1998, 1999; Lai et al., in press) and those of Seyika et al. (1996; Sekiya et al., 1994), which appear to be in direct opposition to the results of Wulf and colleagues (Wulf, 1992b; Wulf et al., 1993). It is important theoretically because our aim in the present experiments was to determine the general prin-

ciples that govern relative- and absolute-timing learning across paradigms. To accomplish this, we conducted two experiments that examined the importance of two specific issues pertaining to relative- and absolute-timing learning: specificity and the scheduling of variable practice, and the nature of the relative-timing feedback provided to the learner. The results confirmed that each of those manipulations plays a role in determining relative-timing performance and learning. The specific nature of those effects has been described in some detail in previous sections of this article. Thus, at this point it is important that we consider the impact of the present data in the more general context of (a) factors that affect relative-timing learning, (b) factors that affect absolute-timing learning, and (c) the dissociation of relative- and absolute-timing learning. Finally, we delineate a new proposal in which we distinguish between the independence of GMP and parameter memory constructs and the interdependence of relative- and absolute-timing memory development.

### Factors Affecting Relative-Timing (GMP) Learning

GMP performance and learning were inferred in the present experiments and in those of Lai and colleagues (Lai & Shea, 1998, 1999; Lai et al., in press) from relative-timing errors. Other researchers have used relative-timing errors and residual root mean square error (*RMSE*), depending on whether the movement was evaluated on the basis of discrete (Wulf, 1992b; Wulf et al., 1994) or continuous (Whitacre & Shea, 2000; Wulf & Schmidt, 1989; Wulf et al., 1993) analyses. In addition, Sekiya et al. (1996; Sekiya et al., 1994) used relative mean velocity in their experiments to characterize GMP performance. Those measures of GMP errors provide a ratio scale assessment of deviations in the relative-timing pattern of the participant from the specified (goal) relative-timing pattern that are useful in determining the subtle changes that occur 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 (Wright & Shea, in press), practice (Whitacre & Shea, 2000), reduced KR frequency (Lai & Shea, 1998; Lai et al., in press; Wulf, 1992b; Wulf et al., 1993), bandwidth KR (Lai & Shea, 1999; Lai et al., in press), contextual interference (Experiments 1 and 2; Sekiya et al., 1996; Sekiya et al., 1994; Wulf, 1992b), and the nature of the feedback (relative vs. absolute) provided (Experiment 2; Wulf et al., 1993).

We have consistently demonstrated across experimental manipulations that factors that promote trial-to-trial consistency in the relative-timing pattern (e.g., constant and blocked practice vs. serial or random practice, reduced KR frequency vs. 100% KR in variable practice, and bandwidth KR in variable practice) enhance relative-timing (GMP) learning when the segmental movement goals and feedback are presented as ratios (i.e., relative time). However, when the segment goals and segment feedback are expressed in terms of segment movement times random practice appears

to better promote relative-timing (GMP) learning than blocked practice does. The dramatic reversal of effects appears on the surface to present a serious contradiction to the consistency hypothesis. However, the results of Experiment 2 demonstrated that when segment goals and feedback are presented as segment times, random practice generally results in more consistent relative-timing patterns in practice than blocked practice does. That was most clearly illustrated when the blocked–segment time group was required to transfer from the first to the second task. That transition resulted in substantial variability in the relative-timing pattern. Thus, it appears that factors that promote consistency in the relative-timing pattern, independent of the variability of practice conditions, tend to enhance relative-timing learning.

In addition, we have argued (Experiment 2) that in blocked practice, where cognitive demands are generally thought to be relatively low, ratio goals and feedback are extremely helpful in terms of relative-timing learning, but those goals and feedback may be overwhelming for participants in random practice groups, where the cognitive demands are thought to be relatively high. In both the elaboration hypothesis (Shea & Morgan, 1979; Shea & Zimny, 1983, 1988) and the reconstruction hypothesis (Lee & Magill, 1983, 1985), it is predicted that random practice will place relatively higher cognitive demands on the participant than blocked practice. Indeed, researchers have demonstrated (Wright et al., 1992; Wulf et al., 1998) that asking participants to engage in additional processing is detrimental to the performance of random practice groups but facilitates that of blocked practice groups. Thus, relative-timing learning may be sacrificed when additional cognitive demands are added to the already high demands imposed by random practice. In contrast, ratio feedback may explicitly communicate the common features of the task variations in blocked practice, where sufficient cognitive resources are available to translate the ratio information. In fact, the ratio information may actually promote inter-item processing (Shea & Morgan, 1979; Shea & Zimny, 1985, 1988). When segment goals and feedback are presented as segment times rather than ratios, the added demands placed on the random practice participants by the feedback may be reduced to a more manageable level because segment and overall goals and feedback are presented in the same metric. In contrast, the blocked practice group, when presented segment time goals and feedback, might have a much more difficult time than the random practice group in determining the underlying relative-timing structure common to the task variations. The structure might become obvious under those feedback conditions only when the participants are faced with random practice.

### Factors Affecting Absolute-Timing (Parameter) Learning

Absolute-timing (parameter) learning appeared to be relatively unaffected by the manipulations of the relative-tim-

ing feedback (Experiment 2). Similarly, a number of researchers (Lai & Shea, 1998, 1999; Lai et al., in press; Wulf, 1992b; Wulf et al., 1993; also see Wright & Shea, in press) have consistently demonstrated that manipulations of reduced frequency or bandwidth relative-timing KR have little, if any, affect on absolute-timing learning. In addition, Wulf et al. (1994) have demonstrated that reduced frequency of absolute-timing feedback does not influence absolute-timing errors, as compared with the provision of 100% absolute-timing KR frequency. Recently, Wright and Shea (in press) demonstrated that although making the relative-timing structure more or less difficult has a substantial impact on relative-timing learning, it does not affect the resultant absolute-timing errors.

A consistent finding in our experiments and in those of Wulf and colleagues<sup>3</sup> has been that serial and random practice schedules are more conducive to absolute-timing learning than are constant or blocked practice schedules, at least as indicated by transfer performance. We argue that this finding is generally consistent with results of experiments reported in the traditional CI literature, in which error measures reflecting absolute time (e.g., Lee & Magill, 1983; Shea & Morgan, 1979) or absolute force (e.g., Shea, Kohl, & Indermill, 1990) have often been used. Thus, the only consistent absolute-timing finding is that scheduling variability in serial or random practice formats where absolute-timing requirements change from trial to trial enhances absolute-timing learning, in contrast to constant or blocked practice, where absolute-timing requirements generally do not change from trial to trial. That finding is contrary to the strict interpretation of the variability of practice hypothesis (see Lee, Magill, & Weeks, 1985, and Shapiro & Schmidt, 1982, for reviews) that is a direct outgrowth of schema theory (Schmidt, 1975, 1988). In that theoretical framework, it is proposed that the ability to parameterize a movement sequence is a product of the range of practice variability without regard to the scheduling of the variability. Our results suggest that the way in which the parameter variability (absolute time requirements) is scheduled does affect absolute-timing learning.

### **Dissociation of Relative- (GMP) and Absolute- (Parameter) Timing Learning**

A general tenet of Schmidt's schema theory (1985, 1988) is that the theoretical constructs, GMP and parameter (or parameters), governing programmed actions are controlled by independent memory states. Until recently, the major evidence in support of the dissociation was that movements could be varied along temporal, spatial, or force dimensions while the structure of the movement remained essentially invariant (Gentner 1987, 1988; Heuer, 1988; Schmidt, 1985; see Wulf et al., 1993, for a discussion of dissociation). However, in more recent experiments, beginning with Wulf and Schmidt (1989), performance has been partitioned into relative-timing, force, or spatial error measures of GMP error, and absolute time, force, or spatial error measures of para-

meter error. The results of 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. In the present experiments, in which we manipulated practice schedule (Experiment 1) and type of relative-timing feedback (Experiment 2), we also found that factors that affect relative-timing learning have relatively little effect on absolute-timing learning. In general, compared with blocked (or constant) practice conditions, random (or serial) practice conditions resulted in enhanced absolute-timing learning, as indicated by delayed transfer tests, regardless of the experimental manipulation imposed by the relative-timing pattern.

Consistent with that position, Lai et al. (2000) recently demonstrated that relative- and absolute-timing errors are not correlated with each other, but are highly correlated with a global error measure. A regression analysis of the data Lai et al. (2000) obtained from manipulated practice schedules (constant and serial) and KR condition (50% and 100%) confirmed that relative- and absolute-timing errors independently contribute (i.e., statistically) to the global error measure: Respectively, 95% and 98% of the variance was accounted for in the global error measure in Experiments 1 and 2. In addition, in a number of other theoretical perspectives on the control and learning of motor sequences it is argued that the processing of the sequence, per se, is independent of the processing of the elements composing the sequence (e.g., Keele, Jennings, Jones, Caulton, & Cohen, 1995; Klapp, 1995, 1997; also see Keele, Cohen, & Ivry, 1990, and Sternburg, Knoll, & Turlock, 1990, for a discussion).

Taken together those findings provide strong support for the empirical dissociation of the memories governing GMP and parameter learning. In future research, we need to aim at determining factors (e.g., practice schedule, feedback condition) that can optimize both relative- and absolute-timing learning (see Lai et al., 2000; Park, Shea, & Wright, 2000; Shea, Wulf, Park, & Gaunt, in press). To date, many of the manipulations that have been experimentally tested have resulted in the enhancement of either the relative or the absolute timing, but rarely in both, and often improvement in one is achieved at the expense of the other. Based on the findings of Roth (1988), suggesting a hierarchy in the development of the GMP structure and parameter rule, Lai et al. (2000) found that providing constant practice early in acquisition so as to promote movement consistency and variable practice later in practice so as to enhance the rule for specifying the parameters results in optimized relative- and absolute-timing learning. One could make a further, and perhaps more stringent, test of dissociation by assessing the degree to which individuals can apply an absolute-timing (parameter) rule, developed on the basis of one relative-timing pattern (GMP), to a novel movement that has a different relative-timing structure. If GMP and parameter memory states are truly dissociated, the 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.

### The Interdependence of Relative- (GMP) and Absolute- (Parameter) Timing Memory Development

In the previous section, we argued that there is substantial evidence that suggests the independence between the memory states that govern relative and absolute timing. It is clear, however, that variability within acquisition blocks, as in serial and random practice, retards the development of the relative timing when segmental goals are presented as segment ratios (Experiment 1) but enhances the development of the relative-timing pattern when segmental movement time goals and feedback are presented (Experiment 2). The opposite is true for constant and blocked practice, even though variability is introduced in blocked practice but not in constant practice. What is not apparent, at least at first glance, is that investigators created variability in many experiments, including the present experiments, by changing the absolute-timing requirements and not the relative-timing requirements. Yet that manipulation has substantial influence on relative-timing learning. That is, constant, blocked, serial, and random practice in the present experiments all resulted in constant practice on the relative-timing pattern; we created and scheduled variability by manipulating absolute timing. That suggests that the manipulation of the 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 independent memory states but may be interdependent in terms of the development of those memory states.

### NOTES

1.  $M$  = mean, and  $SE_M$  = standard error of the mean.

2. Wulf and Lee (1993) have proposed that in many of the traditional CI experiments, global error measures were used that would not allow either GMP or parameter learning to be assessed in a relatively direct way. To the contrary, we propose that in many of the earlier experiments in both the KR and CI literatures, endpoint measurements of performance were used that are relatively straightforward measures of parameter performance. One exception to that point is that relatively few experiments have been conducted on waveform-reproduction tasks, in which root mean square error can be used in the assessment of performance (e.g., Winstein & Schmidt, 1990; Wulf, 1992a).

3. Whereas Wulf and colleagues have tended to find enhanced parameter learning for random or serial practice, compared with blocked practice, those effects have generally not been significant in their experiments.

### REFERENCES

Carnahan, H., VanEerd, D. L., & Allard, F. (1990). A note on the relationship between task requirements and the contextual interference effect. *Journal of Motor Behavior*, 22, 159–169.

Chamberlin, C. I., & Magill, R. A. (1992). A note on schema and exemplar approaches to motor skill representation in memory.

*Journal of Motor Behavior*, 24, 221–224.

Gabriele, T. E., Hall, C. R., & Buckolz, E. E. (1987). Practice schedule effects on the acquisition and retention of a motor skill. *Human Movement Science*, 6, 1–16.

Gabriele, T. E., Hall, C. R., & Lee, T. D. (1989). Cognition in motor learning: Imagery effects on contextual interference. *Human Movement Science*, 8, 227–245.

Gabriele, T. E., Lee, T. D., & Hall, C. R. (1991). Contextual interference in movement timing: Specific effects in retention and transfer. *Human Movement Science*, 20, 177–188.

Gentner, D. R. (1987). Timing of skilled motor performance: Tests of the proportional duration model. *Psychological Review*, 94, 255–276.

Gentner, D. R. (1988). Observed movements reflect both central and peripheral mechanisms: A reply to Heuer. *Psychological Review*, 95, 558.

Hall, K. G., & Magill, R. A. (1995). Variability of practice and contextual interference in motor skill learning. *Journal of Motor Behavior*, 27, 299–309.

Heuer, H. (1988). Testing the invariance of relative timing: Comments on Gentner (1987). *Psychological Review*, 95, 552–557.

Horak, M. (1992). The utility of connectionism for motor learning: A reinterpretation of contextual interference in movement schemas. *Journal of Motor Behavior*, 24, 58–66.

Keele, S. W., Cohen, A., & Ivry, R. (1990). Motor programs: Concepts and issues. In M. Jeannerod (Ed.), *Attention and performance XIII* (pp. 77–110). Hillsdale, NJ: Erlbaum.

Keele, S. W., Jennings, P., Jones, S., Caulton, D., & Cohen, A. (1995). On the modularity of sequence representation. *Journal of Motor Behavior*, 27, 17–30.

Klapp, S. (1995). Motor response programming during simple and choice reaction time: The role of practice. *Journal of Experimental Psychology: Human Perception and Performance*, 21, 1015–1027.

Klapp, S. T. (1997). Reaction time analysis of central motor control. In H. N. Zelaznik (Ed.), *Advances in motor learning and control*. Champaign, IL: Human Kinetics.

Lai, Q., & Shea, C. H. (1998). Generalized motor program (GMP) learning: Effects of reduced frequency of knowledge of results and practice variability. *Journal of Motor Behavior*, 30, 51–59.

Lai, Q., & Shea, C. H. (1999). Bandwidth knowledge of results enhances generalized motor program learning. *Research Quarterly for Exercise and Sport*, 70, 79–83.

Lai, Q., Shea, C. H., & Little, M. (in press). Effects of modeled auditory information on a sequential timing task. *Research Quarterly for Exercise and Sport*.

Lai, Q., Shea, C. H., Wulf, G., & Wright, D. L. (2000). Optimizing generalized motor program and parameter learning. *Research Quarterly for Exercise and Sport*, 71, 10–24.

Lee, T. D., & Magill, R. A. (1983). The locus of the contextual interference in motor-skill acquisition. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 9, 730–746.

Lee, T. D., & Magill, R. A. (1985). Can forgetting facilitate skill acquisition? In D. Goodman, R. B. Wilberg, & I. M. Franks (Eds.), *Differing perspectives in motor learning, memory, and control* (pp. 3–22). Amsterdam: North-Holland.

Lee, T. D., Magill, R. A., & Weeks, D. J. (1985). Influence of practice schedule on testing schema theory predictions in adults. *Journal of Motor Behavior*, 17, 283–299.

Limons, E., & Shea, J. B. (1988). Deficient processing in learning and performance. In A. M. Colley & R. J. Beech (Eds.), *Cognition and action in skilled behavior* (pp. 333–347). Amsterdam: North-Holland.

Magill, R. A., & Hall, K. G. (1990). A review of the contextual interference effect in motor skill acquisition. *Human Movement Science*, 9, 241–289.

Park, J., Shea, C. H., & Wright, D. L. (2000). Reduced frequency

- concurrent and terminal feedback: A test of the guidance hypothesis. *Journal of Motor Behavior*, 32, 287–296.
- Roth, K. (1988). Investigations on the basis of generalized motor programme hypothesis. In O. G. Meijer & K. Roth (Eds.), *Complex movement behavior: The motor action controversy* (pp. 261–288). Amsterdam: North-Holland.
- Schmidt, R. A. (1975). A schema theory of discrete motor skill learning. *Psychological Review*, 82, 225–260.
- Schmidt, R. A. (1985). The search for invariance in skilled movement behavior. *Research Quarterly for Exercise and Sport*, 56, 188–200.
- Schmidt, R. A. (1988) *Motor learning and control: A behavioral emphasis* (2nd ed.). Champaign, IL: Human Kinetics.
- Schmidt, R. A. & Lee, T. D. (1999). *Motor control and learning: A behavioral emphasis*. Champaign, IL: Human Kinetics.
- Sekiya, H., Magill, R. A., & Anderson, D. I. (1996). The contextual interference effect in parameter modifications of the same generalized motor program. *Research Quarterly for Exercise and Sport*, 67, 59–68.
- Sekiya, H., Magill, R. A., Sidaway, B., & Anderson, D. I. (1994) The contextual interference effect for skill variations from the same and different generalized motor programs. *Research Quarterly for Exercise and Sport*, 65, 330–338.
- Shapiro, D., & Schmidt, R. A. (1982). The schema theory: Recent evidence and developmental implications. In J. A. S. Kelso & J. E. Clark (Eds.), *The development of movement control and coordination* (pp. 113–150). New York: Wiley.
- Shea, C. H., Kohl, R. M., & Indermill, C. (1990). Contextual interference: Contributions of practice. *Acta Psychologica*, 73, 145–157.
- Shea, C. H., Wulf, G., Park, J., & Gaunt, B. (2001). Effects of an auditory model on the learning of relative and absolute timing. *Journal of Motor Behavior*, 33, 127–138.
- Shea, J. B., & Morgan, R. L. (1979). Contextual interference effects on the acquisition, retention, and transfer of a motor skill. *Journal of Experimental Psychology: Human Learning and Memory*, 5, 179–187.
- Shea, J. B., & Zimny, S. T. (1983). Context effects in memory and learning movement information. In R. A. Magill (Ed.), *Memory and control of action* (pp. 345–366). Amsterdam: North-Holland.
- Shea, J. B., & Zimny, S. T. (1988). Knowledge incorporation in motor representation. In O. J. Meijer & K. Roth (Eds.), *Complex movement behavior: The motor-action controversy* (pp. 289–314). Amsterdam, North Holland.
- Sternberg, S., Knoll, R. L., & Turock, D. L. (1990). Hierarchical control in the execution of action sequences: Tests of two invariance properties. In M. Jeannerod (Ed.), *Attention and performance XIII* (pp. 77–110). Hillsdale, NJ: Erlbaum.
- Whitacre, C., & Shea, C. H. (2000). The performance and learning of generalizable motor programs: Relative (GMP) and absolute (parameter) errors. *Journal of Motor Behavior*, 32, 163–175.
- Winstein, C. J., & Schmidt, R. A. (1990). Reduced frequency of knowledge of results enhances motor skill acquisition. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 16, 677–691.
- Wright, D. L. (1991). The role of intratask and intertask processing in acquisition and retention of motor skills. *Journal of Motor Behavior*, 23, 139–145.
- Wright, D. L., Li, Y., & Whitacre, C. (1992). The contribution of elaborative processing to the contextual interference effect. *Research Quarterly for Exercise and Sport*, 63, 30–37.
- Wright, D. L., & Shea, C. H. (in press). Manipulating generalized motor program difficulty during blocked and random practice does not affect parameter learning. *Research Quarterly for Exercise and Sport*.
- Wulf, G. (1992a). Reducing knowledge of results can produce context effects in movements of the same class. *Journal of Human Movement Studies*, 22, 71–84.
- Wulf, G. (1992b). The learning of generalized motor programs and motor schemata: Effects of KR relative frequency and contextual interference. *Journal of Human Movement Studies*, 23, 53–76.
- Wulf, G., & Lee, T. D. (1993). Contextual interference in movements of the same class: Differential effects on program and parameter learning. *Journal of Motor Behavior*, 25, 254–263.
- Wulf, G., Lee, T. D., & Schmidt, R. A. (1994). Reducing knowledge of results about relative versus absolute timing: Differential effects on learning. *Journal of Motor Behavior*, 26, 362–369.
- Wulf, G., Lee, T. D., & Schmidt, R. A. (1998). *A motivational hypothesis for contextual interference effects*. Manuscript submitted for publication.
- Wulf, G., & Schmidt, R. A. (1989). The learning of generalized motor programs: Reducing the relative frequency of knowledge of results enhances memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 15, 748–757.
- Wulf, G., & Schmidt, R. A. (1994). Feedback-induced variability and the learning of generalized motor programs. *Journal of Motor Behavior*, 26, 348–361.
- Wulf, G., Schmidt, R. A., & Deubel, H. (1993). Reduced feedback frequency enhances generalized motor program learning but not parameterization learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 19, 1134–1150.
- Young, D. E., Cohen, M. J., & Husak, W. S. (1993). Contextual interference and motor skill acquisition: On the processes that influence retention. *Human Movement Science*, 12, 577–600.

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