Journal of Experimental Psychology:
Learning, Memory, and Cognition
1989, Vol. 15, No. 4, 748–757

0278-7393/89/$00.75

The Learning of Generalized Motor Programs: Reducing the Relative Frequency of Knowledge of Results Enhances Memory

Gabriele Wulf
Institute of Safety and Systems Management
University of Southern California

Richard A. Schmidt
University of California, Los Angeles

In earlier studies, reducing the relative frequency of knowledge of results (KR) enhanced retention of single movements. In the experiments here we asked whether this variable also enhances memory for classes of actions governed by generalized motor programs. Acquisition conditions involved practicing three versions of a sequential timing task. All three versions had the same temporal structure (or phasing), but the overall durations were different. KR was presented on either 100% or 67% of the trials for two groups. In Experiment 1, reduced relative KR frequency, spread equally across all task versions, enhanced accuracy of the learned relative timing structure as measured on a transfer test with a novel movement duration. Experiment 2 showed that retention of a medium-duration version was more accurate for subjects who never received KR about it in acquisition, as compared with subjects who always did. The data support the view that reduced KR frequency enhances acquisition of the relative-timing structure underlying memory for a class of actions.

It has long been recognized that one of the most important variables that determine motor skill learning is the information feedback provided to the performer during practice (e.g., Bilodeau & Bilodeau, 1961; Newell, 1976a; Salmoni, Schmidt, & Walter, 1984; Schmidt, 1988). Feedback about the outcome of a movement—usually termed *knowledge of results* (KR) in the research literature—has been thought to function in various ways, such as guiding the learner to the goal movement (e.g., Adams, 1971), increasing the capability to define schemata for the production of novel actions (Schmidt, 1975), and as generally leading to the establishment of permanent memory capabilities. The traditional viewpoint about the functioning of KR for motor learning that prevailed from the time of Thorndike (1927) through the 1970s generally holds that any variables making KR more frequent, more precise, more immediate, and more informationally "rich" will enhance learning. This view also holds that trials that do not receive KR are either "neutral" with respect to learning (Schmidt, 1975; Thorndike, 1927) or are detrimental to the acquisition process (Adams, 1971). These general views about how KR functions for motor learning—simply, that more KR is always more effective for learning—have dominated thinking with respect to practical application in instructional settings and in simulator design.

However, this long-standing position about the principles of KR has been challenged recently by Salmoni et al. (1984). In their review of the KR literature, they identified several earlier experiments that seemed to violate this general view or at least to challenge it strongly. Several studies show that, relative to KR conditions that would appear to be maximally informative for motor learning, certain KR variations that acted to systematically degrade performance improvement during the acquisition phase when KR was present and being manipulated actually enhanced performance in retention tests, chiefly those for which KR had been removed. Salmoni et al. argued that these KR variations degraded *performance* improvement during the period when KR was present but actually enhanced *learning*, as measured on these retention tests (see Salmoni et al., 1984, for a more complete treatment of the performance vs. learning effects of KR). These kinds of findings seemed to provide considerable difficulty for the earlier generalizations about KR's functioning and served as the motivation for additional work here on these variables.

This more recent work has, in fact, tended to support these earlier suspicions. For example, following the lead provided by Lavery (1962), several experiments examined *summary KR*, where feedback about each of a set of trials (e.g., 10) is provided only after the last trial in the set has been completed. Relative to providing KR after each trial (essentially a 1-trial summary), increasing the summary length—that is, the number of trials described by the summary—in the acquisition phase when KR is present and being manipulated generates substantial decrements in performance improvement. Providing the information about a given trial only after several others seemed to decrease the informational utility of the KR here. However, summary KR conditions produced more effective no-KR retention performance, particularly when the retention test was delayed (Schmidt, Shapiro, Winstein, Young, & Swinnen, 1987; Schmidt, Young, Swinnen, & Shapiro, 1989).

Another variable that has been studied in this context is the *relative frequency*—or the proportion of trials in a practice period for which KR is provided. Winstein (1988; Winstein & Schmidt, 1988) has recently examined a 50% KR condition in a complex lever-patterning task. This 50% condition had

This research was supported by Contract MDA903-85-K-0225 from the U.S. Army Research Institute (Basic Research) to Richard A. Schmidt and D. C. Shapiro and by a postdoctoral grant from the Deutsche Forschungsgemeinschaft (Grant II 0 2–Wu 141/2-1) to Gabriele Wulf.

Correspondence concerning this article should be addressed to Gabriele Wulf, Institute of Safety and Systems Management, University of Southern California, Los Angeles, California 90089-0021.

KR *faded* across practice so that the relative frequency of KR in early practice was 100%, decreasing systematically to 20% at the end of each practice day. Compared with a 100% KR condition, the 50% faded condition showed a small tendency for more effective performance during the acquisition phase when KR was present and being manipulated but much more effective performance in both KR and no-KR retention tests, particularly after longer retention intervals. Thus, surprisingly, these data show that *fewer* KR presentations led to increased learning, as it is measured by the capability to retain under various feedback conditions (see also Young, 1988). These studies provided the motivation for the experiments reported here.

These recent experiments on KR have shown that at least some KR conditions that degrade the performance improvement in the acquisition phase seem to have the effect of increasing performance in various kinds of retention tests, particularly when the retention test is delayed. It is as if the conditions that make KR "difficult" to use in acquisition (e.g., long KR summaries and low relative frequencies) produced a durable memory representation that was evidenced when performance was demanded on a retention test. These studies support a *guidance hypothesis* for KR (Salmoni et al., 1984), according to which KR that is "too easily" used in acquisition results in effective performance in acquisition because of KR's strong informational (or guiding) properties but produces a kind of reliance on it that causes performance to be poor in retention, particularly when KR is removed there.

These previous studies have been concerned chiefly with the learning of single movement skills. However, throughout the last decade or more, there has been a considerable emphasis on the idea that motor learning involves the acquisition of *classes* of activities. In one version of this idea (Schmidt, 1975, 1988), at least some kinds of skills are based on learning of generalized motor programs. These programs are assumed to have a rigidly defined temporal structure (or phasing), so that the *relative timing* among the components of these actions is invariant (e.g., Schmidt, 1975, 1985). With this invariance, the ratios of the durations of any two segments within a movement (or the ratio of any segment to the total duration of the movement) should be constant, even though the total duration of the movement may vary freely across relatively wide limits. Thus, the overall duration of the action is governed by a parameter applied to the generalized motor program, but the temporal structure is invariant as defined by the relative timing in the program.

The learning of these generalized motor programs is the focus of the present experiments. Although considerable attention has been directed toward how subjects learn to parameterize these programs to achieve particular environmental goals (e.g., the learning of a particular movement time value; see Shapiro & Schmidt, 1982, for a review), there has been almost no concern for the learning of the patterns of action themselves (see Heuer & Schmidt, 1988, and Swinnen, 1987, for exceptions). Therefore, in the present experiments we asked whether the principles of KR for the acquisition of single actions (described earlier) would parallel those for the acquisition of generalized motor programs.

Specifically, we asked whether a reduced relative frequency of KR—which enhances retention performance in single actions—would have similar effects on the acquisition of classes of actions represented by the generalized motor program. For example, a task might require "dialing" a number on a push-button telephone in a certain rhythm (relative timing), but with different task versions having different overall durations (absolute timing). Performance can be assessed in terms of accuracy in overall duration (of a specific task version) or in terms of accuracy in relative timing that is common to all versions. In contrast to previous studies, the focus here was on the learning of the relative timing structure—which underlies a whole class of movements—rather than the overall duration, or absolute timing, of a specific single movement. The general method was to manipulate the relative KR frequency in various ways during practice of movements with the same relative timing (but with different overall timing). We then examined retention either on (a) a novel movement variant where the overall movement time was different from that learned in acquisition but where the relative timing was the same or (b) a practiced movement variant that was practiced earlier in the acquisition phase.

Experiment 1

In this experiment, three versions of a given movement pattern were practiced in an acquisition phase, where one group received a relative KR frequency of 100% and another received KR on a 67% faded schedule. The important criterion to demonstrate the learning of generalized motor programs is the performance on a *novel* task version, where the relative timing is the same as in acquisition, but the overall movement time is different. Thus, of particular focus is the performance on a criterion test in which retention of the learned relative timing, but transfer to a novel absolute timing, is required. If reduced relative frequency and faded KR, in fact, enhance learning of generalized motor programs, the 67% KR group should perform more effectively on this transfer test.

Method

Subjects. Undergraduate kinesiology students (16 female, 10 male) from the University of California, Los Angeles, served as subjects in exchange for course credit. All were naive as to the purpose of the experiment and had no prior experience with the experimental apparatus.

Apparatus. An illustration of the apparatus used is provided in Figure 1. It consisted of a wooden board in which four microswitches were embedded, with buttons (2.5 cm in diameter) attached to each actuating arm. The microswitches were wired with three digital millisecond timers so that the first timer was started when the first button was released and stopped when the second button was pressed. Pushing the second button also started the second timer, which stopped when the third button was pressed. The third button started the third timer, which stopped when the fourth button was pressed. The millisecond timers were located directly behind the board, visible to the subjects.

Procedure and task. The task required subjects to push the four buttons in the prescribed sequence (see Figure 1) and to be as accurate

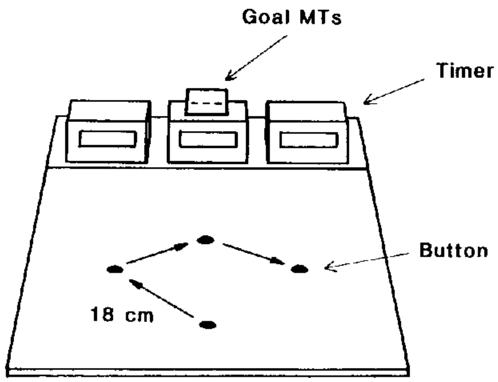

Figure 1. Illustration of apparatus used from the perspective of the subject. (MT = movement time.)

as possible with respect to the goal movement times (MTs) for the three segments (Segment 1 was from the first to the second button press; Segment 2 was from the second to the third button press; Segment 3 was from the third to the fourth button press). Subjects began each trial with their hand resting on the board; as soon as they were ready they lifted their hand and started moving, pressing the buttons with the index finger. The goal MTs for each of the three segments were presented to the subjects by means of cards mounted above the apparatus. KR in terms of the actual MTs for each segment in milliseconds was available instantaneously after each trial.

Subjects practiced three task versions with the same relative timing. That is, the relations among the goal segment times remained constant across task versions, namely 1:2:1.5. The absolute goal segment MTs (in milliseconds) for the three versions (a, c, and d) were 180-360-270, 240-480-360, and 270-540-405, respectively. (Version b was used in the transfer phase and is described below.) Each version was performed six times before subjects were switched to another version. The different task versions were presented randomly, with the restriction that each version occur once within three consecutive blocks. At the beginning of acquisition subjects were shown the goal MTs for the three practice task versions. They were not explicitly informed that the relation among the segment times was identical for all versions; however, they probably recognized this characteristic relatively easily.

The subjects were randomly assigned to two groups of 13 subjects each. A 100% KR group received KR about each segment after every trial, whereas the 67% KR group received KR only on two thirds of the trials. Moreover, in the 67% relative frequency condition, KR was administered in terms of a fading schedule; that is, the relative frequency of KR was systematically reduced across the acquisition phase, as Winstein (1988) has done. Specifically, KR was withheld on one out of six trials during the first third of the practice phase, on two out of six trials during the second third, and on three out of six trials during the last third, producing an *average* relative frequency of 67%. Within a block of six trials (on the same task version), during the first third of practice there was no KR on the fifth trial; during the second third there was no KR on the fourth and fifth trial; and during the last third of practice there was no KR on the third, fourth, and fifth trial. Thus, KR was always provided on the last trial of each block, giving subjects some information about the errors made on the preceding no-KR trial(s). Subjects were informed about the scheduling of KR (for their respective condition) before the beginning of acquisition and about the presence of a transfer test on a novel task version.

The experiment consisted of three phases: acquisition on Day 1, immediate transfer on Day 1, and delayed transfer 24 hr later. During *acquisition* all subjects performed 108 practice trials. Each version (a, c, and d) was performed six times in a row, with 18 blocks of six practice trials. Directly following the acquisition phase, both groups performed 18 no-KR transfer trials (*immediate transfer*) on a novel task (Version b) with the same relative timing but an absolute duration (i.e., 210-420-315) not practiced earlier. On the following day, all subjects again performed 18 trials without KR on the same transfer task as on Day 1 (*delayed transfer*). Again, subjects were not informed that the relative timing of the transfer task was the same as during acquisition, but they undoubtedly realized it quickly.

Statistical analyses. Generalized motor programs are assumed to have invariant relative timing, so that any movement produced using the program will have the same temporal organization. In addition, the duration of any given movement (and all its segments) could be long or short, as defined by particular parameter values assigned to the program. Our goal here was to define dependent measures which reflect the "strength" or "accuracy" of the fundamental temporal structure. One possible measure involves the accuracy of the obtained *segment durations* as compared with the goal segment durations. This method has the drawback, however, that it confounds errors in program structure with errors in the selection of parameters.[1] For this reason, we chose to use errors in the *proportions* of the total movement time occupied by each of the movement segments as the dependent measures here.

These errors in achieving the goal proportions of the three segments (the goal proportions were .222, .444, and .333) were computed for each trial in a six-trial block, where the goal absolute durations of the segments were constant. Several summary measures of these proportions were then computed within subjects across the six trials. First, we computed the (actual) mean proportions for each of the three segments in these six movements (e.g., .189, .467, and .344). These are analogous to constant error (*CE*) measures of bias in more traditional analyses of error scores (e.g., −.033, .023, and .011). However, these *CE* measures have the difficulty that, across subjects, positive values for a given subject tend to "cancel" negative values of another subject (e.g., Newell, 1976b), leading to potentially faulty conclusions about the average bias within a *group* of subjects. For this reason, we also used $|CE|$ values for each subject in these analyses. For a given segment, the average of the six signed values in a block was defined the *CE*; the absolute value of this CE was used as the measure of bias for that segment. This was repeated for the other two segments, and then the $|CE|$s for each of the three segments (e.g., .033, .023, and .011) were averaged across segments to obtain the average $|CE|$ for that block of six trials for that subject (e.g., .022).

Inconsistency of the pattern production—analogous to variable error (*VE*) in more traditional analyses—was assessed by taking the within-subjects standard deviation (*SD*) of the proportions for a given segment, where the *SD* was computed across the six trials in a block. This process was repeated for the second and third segments, resulting in three *SD* values for that block of trials. These *SD*s were then averaged across the three segments to obtain a measure of the average inconsistency of segment proportions in that block of trials for a given subject.

---

[1] Errors in the actual durations of one or more movement segments are a combination of (a) errors in the temporal structure of the action (relative timing) and (b) errors in parameterization (absolute timing). Thus, the interpretation of errors in absolute timing is ambiguous. On the other hand, error in relative timing can be measured directly, is not influenced by errors in absolute timing (parameterization), and is therefore used as a measure of the "strength" of the motor-program representation here.

Results

Acquisition. Figure 2 shows the mean segment proportions, in relation to the goal proportions (i.e., .22, .44, and .33), for the 100% KR and the 67% KR groups during acquisition. Performances were averaged within blocks of 18 trials, each containing three different task versions (a, c, and d). These data provide evidence about any shifts in the temporal structure over practice and indicate the extent to which the subjects acquired the goal movement patterning. As can be seen, both groups performed very similarly. At the beginning of practice, the proportions of the shortest (first) segment and of the medium-duration (third) segment were too long, whereas the proportion of the longest (second) segment was too short. Subjects gradually approached the criterion proportions over the acquisition phase, and on the last block the errors in average proportions for all three segments were almost zero in both groups. The main effect of block was significant for both the first and second segment, $Fs(5, 120) = 15.83$ and 12.57, respectively, $ps < .001$, whereas the block effect failed significance for the third segment, $F(5, 120) = 1.67$, $p > .05$. Neither the main effects of group, $Fs(1, 24) = 0.99$, 0.00, and 1.99, respectively, $ps > .05$, nor the Group × Block interactions were significant, $Fs(5, 120) < 1$. As argued above, however, mean proportions may not be an adequate measure for relative timing performance, and $|CE|$ was used to assess accuracy in relative timing.

$|CE|$ in relative timing during acquisition is shown in Figure 3 (far left). Both groups decreased errors in relative timing across practice, $F(5, 120) = 19.97$, $p < .001$. The 67% KR group apparently required a somewhat larger number of trials than the 100% KR group to reduce their deviations from the goal pattern, as the 67% KR group reached the performance level of the 100% KR group only toward the end of the acquisition phase. The interaction of group and block, $F(5, 120) = 1.54$, $p > .05$, was not significant, however, nor was the main effect of group, $F(1, 24) < 1$.

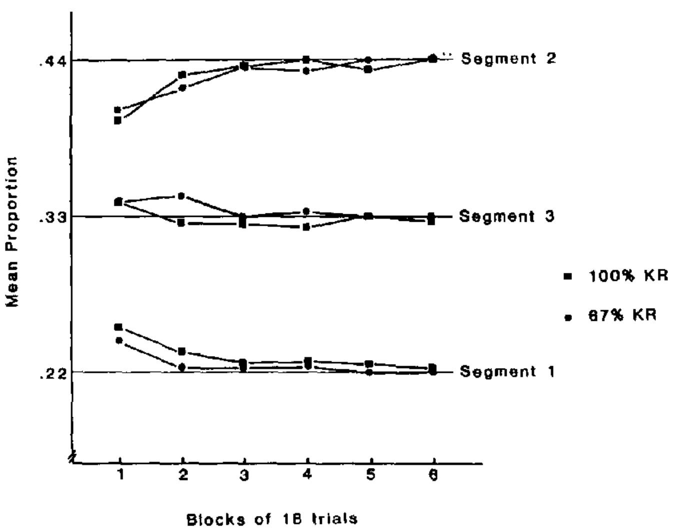

Figure 2. Mean proportions for the three movement segments in acquisition, with each block containing averaged performances on Versions a, c, and d in Experiment 1. (KR = knowledge of results.)

The 100% KR and the 67% KR group performed very similarly with regard to variability (*VE*) in relative timing throughout the acquisition phase. Early in practice, *VE*s were .050 and .049 for the 100% KR and the 67% KR groups, respectively. Both groups reduced their *VE* over acquisition to .036 (i.e., by about 28% and 27%, respectively) by the end of practice. The main effect of block was significant, $F(5, 120) = 9.76$, $p < .001$, whereas the group effect, $F(1, 24) < 1$, and the Group × Block interaction, $F(5, 120) < 1$, were not.

Thus, even though the relative KR frequency was only 67%, systematically reduced from 83% to 50% across practice, the 67% KR group tended to perform with somewhat (nonsignificantly) more bias than the 100% KR group across trials. There was no evidence of poorer performance for stability (*VE*) as relative frequency was reduced.

Immediate transfer. Following acquisition, all subjects performed 18 transfer trials without KR on task Version b with the same relative timing as the practice task versions but with a novel absolute MT (210-420-315); this MT was within the range of MTs experienced earlier in acquisition. The center panel of Figure 3 shows $|CE|$ in relative timing for this immediate transfer test. The 100% KR group showed a slight tendency to improve their relative timing, whereas the 67% KR group remained fairly stable across trial blocks. Overall, the 67% KR group produced a smaller $|CE|$ than the 100% KR group. However, neither the main effects of block, $F(2, 48) < 1$; group, $F(1, 24) < 1$; nor the Group × Block interaction, $F(2, 48) < 1$, were significant.

With regard to *VE* in relative timing, there was no difference between the 100% KR and the 67% KR group at the beginning of transfer, where both groups had a mean *VE* of .028. The 100% KR group remained at this level throughout the transfer phase, while the 67% KR group reduced *VE* slightly to .024 at the end of immediate transfer, but neither the main effect of group, $F(1, 24) < 1$; block, $F(2, 48) < 1$; nor the Group × Block interaction, $F(2, 48) < 1$, was significant.

Delayed transfer. Relative timing performance on delayed transfer—that is, approximately 24 hr later—is shown at the right of Figure 3. The 67% KR group showed no retention loss, relative to the immediate transfer phase, while the 100% KR group demonstrated a clear performance decrement from immediate to delayed transfer. The interaction of transfer phase and group was not significant, however, $F(1, 24) = 2.13$, $p > .05$. Even so, on the delayed test, the 67% KR group was clearly more effective in producing the required relative timing pattern than the 100% KR group, significant with $F(1, 24) = 5.21$, $p < .05$. There was essentially no change in $|CE|$ during the delayed transfer phase for either group, and neither the main effect of block, $F(2, 48) < 1$, nor the Group × Block interaction, $F(2, 48) = 1.49$, $p > .05$, was significant.

Also, the 67% KR group tended to perform more consistently, with *VE* being, on average, 17% smaller than that for the 100% KR group (i.e., .029 vs. .035); this effect failed statistical significance, however, with $F(1, 24) = 2.13$, $p > .05$. Both the 67% KR and the 100% KR group reduced their variability in responding over the course of delayed transfer from .035 to .025, and from .044 to .030, respectively (by about 29% and 33%). The main effect of block was significant,

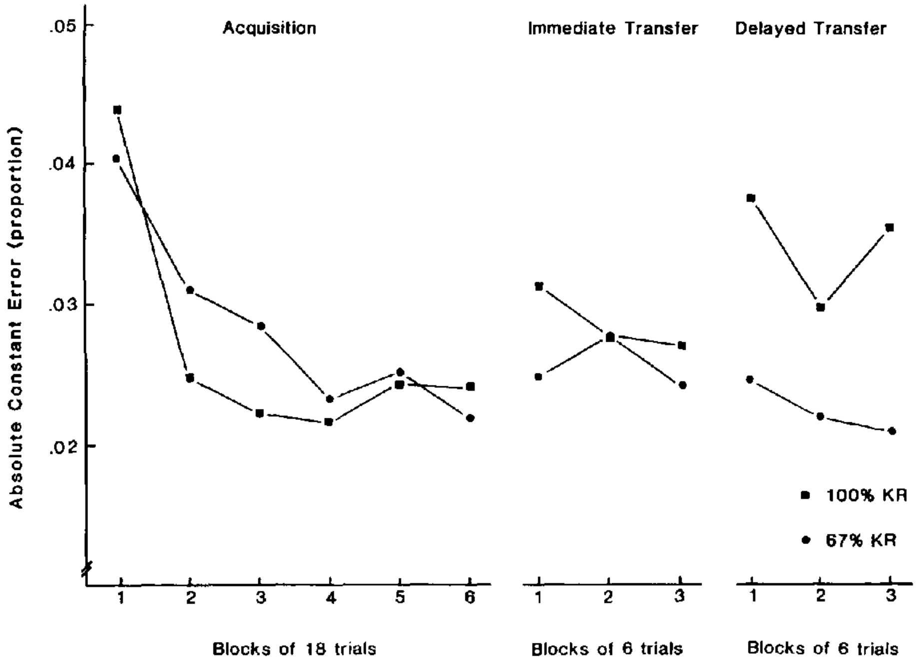

Figure 3. Average absolute constant error in relative timing in acquisition, with each block containing averaged performances on Versions a, c, and d and in immediate and delayed transfer on Version b in Experiment 1. (KR = knowledge of results.)

with $F(2, 48) = 7.87$, $p < .01$, while the Group × Block interaction was not, $F(2, 48) < 1$.

Thus, the 67% KR group which received KR only on two thirds of the acquisition trials performed more effectively than the 100% KR group on the novel task version after 1 day. We interpret this result as showing that subjects acquired the capability to produce a generalized motor program with practice and that reduced relative frequency of KR under a faded schedule enhanced this process.

Discussion

During the acquisition phase, systematically reducing KR (relative to 100% KR) in such a way that the relative frequency of KR was comparatively high (83%) at the beginning of practice and lower toward the end of practice (50%) did not markedly impair performance. Both groups clearly acquired a new, and more accurate, timing pattern over the course of practice. The important criterion providing evidence of the learning of generalized motor programs involved performance on the novel transfer test (Version b). There were essentially no differences between groups on the immediate transfer test. But on the delayed transfer test the 67% KR group was more accurate (in terms of $|CE|$) in producing the required movement pattern than the 100% KR group and was somewhat (although nonsignificantly) more consistent as well. Thus, contrary to earlier viewpoints about KR, providing fewer KRs actually enhanced learning of the overall temporal structure of this action. These data suggest that previous findings demonstrating enhanced learning of single movements by reducing the relative frequency of KR can be generalized to the learning of classes of movements—that is, to the learning of generalized motor programs.

There is one minor concern that must be dismissed before the above interpretation about generalized motor programs can be taken seriously. Strictly, interpretations about learning of generalized motor programs require evidence of positive transfer from the acquisition phase to a novel variant of the class of tasks practiced in acquisition—that is, evidence that the novel-version performance of our 67% KR group (and/or 100% KR group) is more accurate than that for a group of subjects without any previous practice on the surrounding tasks. Thus, strictly, a no-acquisition control condition would be needed. We felt it unnecessary to include this group for several reasons. First, the pattern errors of such a group would almost certainly have exceeded those seen by the 67% KR and 100% KR groups on the *first block* of practice trials, where $|CE|$s were around .04 (Figure 3). On this block, there were no differences in pattern errors for the three versions that were practiced, and there is every reason to suspect that the fourth version (which was embedded within the range of the other three) would have shown similar $|CE|$s as well; also, the "transfer" test for a no-acquisition control condition has *no KR* (whereas Block 1 performances had trials *with* KR), which would have increased errors on such a transfer test even beyond .04 units. Second, the pattern errors of the 67% KR group on the novel transfer test were very similar to those shown for the other patterns at the *end* of practice after considerable improvement had been demonstrated (Figure 3). Third, considerable evidence of positive transfer from practice with a given relative timing on a novel task with the same relative timing (but different movement time) exists in similar tasks (see Shapiro & Schmidt, 1982, for a review), and there is little reason to doubt that it would occur here as well. For these reasons, we conclude that the transfer from the acquisition phase to the novel version of the task was positive and that the omission of a no-practice control condition does not affect the interpretation of this experiment.

As with the previous work on the learning of single actions (Winstein, 1988), these data with faded KR provide challenges to the earlier viewpoints about the functioning of KR in learning. First, although it was a null effect, it is of some interest that the group with only 67% KR was able to perform at least as well during acquisition, and possibly on the immediate transfer test, as a group with 100% KR. Of course, prevailing views of KR would have predicted the 100% KR condition would have been most effective here. The most important finding here was the more accurate performance of the 67% KR group on the delayed test, coupled with essentially no retention losses across the retention interval, which was again contrary to the view that more KR in acquisition will be more effective for learning and retention. This pattern of results agrees reasonably well with that of Winstein (1988) for single movements, who found that differences in favor of a low relative frequency condition with faded KR did not emerge until a 1-day retention test. It would appear that reduced relative frequency (with fading) has its effects primarily on the development of long-term retention capabilities, for both single actions and the classes of actions studied here.

The fading schedule for KR used in the 67% KR group—in which relative frequency was systematically reduced across practice—provides additional support for the guidance hypothesis of KR (Salmoni et al., 1984). According to this hypothesis, the relative frequency of KR should be high early in practice when the learner requires informational guidance to acquire the proper movement pattern. After the pattern has been approximated, however, the learner must not become reliant on the guiding properties of KR, and so the acquisition process should be benefited by the gradual withdrawal of KR across further practice.

Experiment 2

Experiment 1 showed that a reduced relative frequency of KR—uniformly spread across different task versions—can enhance the performance on a novel movement variation. To explore the limits of this kind of effect, Experiment 2 attempted an extreme manipulation of relative frequency. We asked whether reducing the relative frequency of KR to 0% on one task version during acquisition would also lead to enhanced memory, as assessed by a *retention* test on this version. As in Experiment 1, the design included two groups of subjects that practiced the same three versions of the sequential timing task used in the first experiment. Again, all three versions had the same relative timing but different absolute movement durations. The KR group received KR after every trial of each version, while the no-KR group was provided with KR only on two of the three versions and never received KR on the medium-duration (b) version. The question here was whether reducing the KR frequency in this way would lead to enhanced memory for the task, as compared with a 100% KR group.

Method

Subjects. Thirty (19 female, 11 male) undergraduate kinesiology students were used as subjects. None had served in Experiment 1.

Apparatus, procedures, and task. The apparatus, methodological procedures, and task were nearly identical to those used in Experiment 1, except as noted below. Again, subjects practiced three task versions with the same relative timing; the absolute goal segment MTs (in milliseconds) for Versions a, b, and c were 180-360-270, 210-420-315, and 240-480-360, respectively. The subjects were randomly assigned to two groups of 15 subjects each: the KR group and the no-KR group. The KR group received 100% KR on every version, while the no-KR group received 100% KR on both the fast (a) and the slow (c) version, and never received KR on the medium-speed (b) version.

The experiment consisted of three phases: acquisition and immediate retention on the first day, and delayed retention 1 day later. *Acquisition* was identical to that of the first experiment in terms of the number of trials, the block size, and the order of versions; only the absolute movement times of the task versions were partly different (see above). Following acquisition both groups performed 18 retention trials (*immediate retention*) without KR, using the task version with the medium duration (b). *Delayed retention,* approximately 24 hr later, was identical in content to the immediate retention test.

Results

Acquisition. Performances with regard to the mean proportions were very similar for the three task versions, including the no-KR group's performance on the Version b (with 0% KR); therefore, the data for Versions a, b, and c were collapsed for presentation. Figure 4 shows the alterations of the mean segment proportions with practice, in relation to the goal proportions, over the acquisition phase. As in Experiment 1, both groups performed very similarly. The actual proportions of the three segments, while being relatively sim-

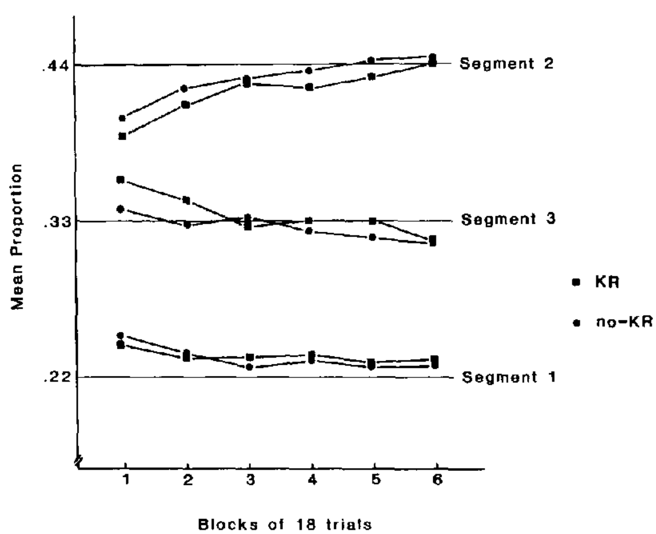

Figure 4. Mean proportions for the three movement segments in acquisition, with each block containing averaged performances on Versions a, b, and c in Experiment 2. (KR = knowledge of results.)

ilar to each other early in practice, diverged in the course of acquisition toward the goal proportions. The main effect of block was significant for the first, second, and third segments, $Fs(5, 140) = 4.88$, 21.73, and 7.87, respectively ($ps < .001$). The group effect was not significant for any segment, $Fs(1, 28) = .04$, 1.20, and 1.71, respectively for Segments 1, 2, and 3 ($ps > .05$). The interaction of group and block was not significant for these segments either, $Fs(5, 140) = 1.31$, 0.33, and 1.49, $ps > .05$.

$|CE|$s in relative timing on the three task versions are shown at the left of Figure 5. Both groups generally reduced their deviations from the required relative timing over the course of acquisition, $F(5, 140) = 20.66$, $p < .001$. Both groups performed similarly on Versions a and c, for which KR was always provided. However, on Version b (where KR was withheld for the no-KR group and was provided for the KR group), the no-KR group not only tended to produce larger $|CE|$s compared with their performances on Versions a and c but also compared with the KR group's performance on Version b. Also, performances on Versions a and c, in general, were not different from each other. A Group × Block × Version analysis of variance (ANOVA) yielded no significant main effects of group, $F(1, 28) < 1$, version, $F(2, 56) < 1$, nor interaction of group and version, $F(2, 56) = 1.53$, $p > .05$.

The groups demonstrated virtually identical variability in responding, with *VE* being .044. Over the course of acquisition, the no-KR and KR groups reduced their *VE* to .030 and .034 (by about 32% and 23%), respectively. The main effect of block was significant, with $F(1, 5) = 6.20$, $p < .001$, while the Group effect, $F(1, 28) < 1$, and the interaction of Group and Block, $F(5, 140) < 1$, were not.

Of special interest here is the no-KR group's acquisition performance on Version b. As can be seen, the no-KR group—without *ever* receiving KR on this version—reduced their $|CE|$ in relative timing on Version b, $F(5, 70) = 2.30$, $p < .05$. They also reduced their *VE* on this task version over the course of acquisition from .041 to .030 (by about 27%), but this effect did not reach statistical significance, $F(5, 70) = 1.88$, $p > .05$. Because this learning would have been unlikely had Version b been presented in isolation without KR (e.g., Bilodeau, Bilodeau, & Schumsky, 1959; Trowbridge & Cason, 1932), these data support the view that this version was being learned through its interactions with Versions a, and c, which did receive KR.

Immediate retention. Directly following Acquisition 1, immediate retention consisted of 18 trials without KR on the medium-speed version, on which the KR group had received 100% KR, and the no-KR group had received 0% KR during practice. Absolute errors in relative timing for the three blocks of trials are shown in the center panel of Figure 5. Although the KR group had clearly less $|CE|$ in relative timing on the last acquisition block of Version b, they demonstrated higher errors than the no-KR group on the first block of the retention phase (on this version); this interaction of group and block was significant, with $F(1, 28) = 4.16$, $p = .05$. Overall, on immediate retention the no-KR group performed more effec-

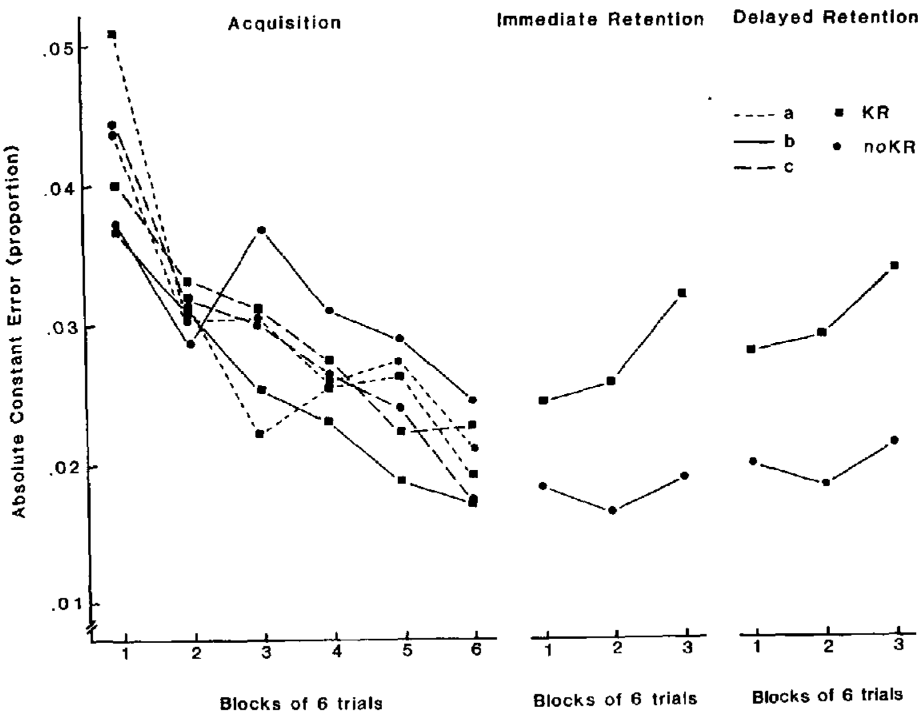

Figure 5. Average absolute constant error in relative timing in acquisition, with each block containing averaged performances on Versions a, b, and c and in immediate and delayed retention on Version b in Experiment 2. (KR = knowledge of results.)

tively than the KR group, with $|CE|$ being 52% higher for the KR group, on average. The main effect of group, however,fell short of the 5% level of significance, $F(1, 28) = 2.75$, $p = .11$. Also, the KR group tended to show a performance decrement over retention blocks, contrary to the no-KR group, which maintained their performance level throughout the immediate retention phase. The interaction of group and block was not significant, though $F(2, 56) < 1$, and neither was the main effect of block $F(2, 56) = 1.93$, $p > .05$.

With regard to the variability in responding, both groups became slightly more consistent over the course of immediate retention. The KR group and the no-KR group reduced their *VE* from .027 at the beginning of the retention phase to .024 and .021 (by about 11% and 22%), respectively, by the end of immediate retention. However, the main effects of group, $F(1, 28) < 1$; block, $F(2, 56) = 1.37$, $p > .05$, and the Group × block interaction, $F(2, 56) < 1$, were not significant.

Delayed retention. In the second test session, 1 day later, subjects again performed 18 trials without KR on the medium-speed version on which the KR and no-KR manipulation had been imposed in acquisition. Relative-timing performance on delayed retention is shown to the right of Figure 5. As during immediate retention, the no-KR group demonstrated clearly more effective performance, with $|CE|$ being51% higher for the KR group; this effect was significant, with $F(1, 28) = 4.38$, $p < .05$. There was a tendency for the KR group to increase $|CE|$ slightly over block, while the no-KR group maintained performance, but this interaction of group and block was not significant, $F(2, 56) < 1$. The effect of block was not significant either, $F(2, 56) < 1$.

Moreover, the no-KR group was more consistent in their relative-timing performance. *VE* was overall about 21.5% smaller than for the KR group, and this effect reached borderline significance, with $F(1, 28) = 3.43$, $p = .07$. The KR group reduced their *VE* from .033 to .024 (about 27%), and the no-KR group from .023 to .021 (about 9%) over delayed retention. The main effect of block was significant, with $F(2, 56) = 8.48$, $p < .001$. No significant Group × Block interaction was found, $F(2, 56) = 1.50$, $p > .05$.

Thus, on delayed retention, the group that had received no KR at all on the criterion task version during acquisition was both more accurate and more consistent in relative timing than the group that had received 100% KR. This suggested that the gains on Version b demonstrated in the acquisition phase were relatively permanent, being demonstrated again in a retention test.

Discussion

The results in acquisition were clear in showing that the no-KR group generally performed less effectively on the task version on which they did not receive KR (Version b) than the KR group with 100% KR. Yet, the no-KR group was able to reduce their $|CE|$s and their *VE*s around the required relative timing on Version b over the course of practice. This improvement on a single task in isolation seems unlikely without KR (e.g., Bilodeau et al., 1959; Trowbridge & Cason, 1932), and there is little reason to believe that such no-KR learning occurred here. Rather, we argue that Version b was learned as part of a *class* of actions including Versions a and c.

However, on the retention test for Version b, the group receiving no KR in acquisition on this version was considerably more accurate and consistent than the group that had always received KR about Version b. Although the group mean values were similar in the two retention tests, these effects were significant only in the delayed retention test, which again tends to support Experiment 1 (and Winstein, 1988) in that the effects of lowered relative frequency of KR were larger in delayed retention tests.

We interpret these retention results for Version b as support for the notion that reduced relative frequency of KR enhanced the learning of the class of movements governed by the imposed relative timing structure. In this view, Version b—being a member of that class—benefited from the reduced KR relative frequency and had more accurate performance on its retention test as a result.

However, at least one objection to this interpretation can be raised. Suppose that, rather than the reduced KR frequency leading to more effective learning of the generalized motor program, this variable may have only emphasized the unique nature of Version b to the subjects. Indeed, this version was the only one without any KR, and it could be argued that this version received some special attention by the subjects, thus allowing them to learn it more effectively. There are several reasons why this single-task interpretation seems incorrect.

First, this notion would expect that subjects would not only perform Version b with more accurate relative timing but also with more accurate absolute timing. In absolute movement duration (*CE*), however, there was essentially no difference between groups in both immediate and delayed retention. Second, as argued above, in view of the research on the learning of single movements without KR (e.g., Bilodeau et al., 1959; Trowbridge & Cason, 1932), it seems unlikely that Version b *by itself* could have been acquired more effectively without KR than with 100% KR. Rather, it seems far more acceptable to believe that the surrounding Versions a and c provided some kind of "support" for the learning of Version b in the no-KR group. Of course, one view is that such support arose from the learning of a class of movements, of which Versions a, b, and c were all members. Finally, these findings are in strong agreement with the reduced relative frequency data from Experiment 1, where transfer to a novel task version was enhanced in the 67% KR group. Thus, the hypothesis that *specific* Version b learning was more effective in the no-KR group in Experiment 2 cannot explain how a *novel* version was performed more effectively in Experiment 1. These arguments do not favor the hypothesis that only Version b was learned more effectively here. Rather, the data tend to support the view that a class of movements was learned and that reducing the relative frequency during practice by withholding KR on one version facilitated this process.

General Discussion

The focus of the present experiments was the learning of generalized motor programs. Even though there has been considerable support for the notion of generalized motor programs which are assumed to govern *classes* of movements with the same temporal structure (see Schmidt, 1975, 1985), there has been little concern for the *learning* of these patterns of action. We asked whether variables that have been shown to enhance the learning of *single* movements (specifically, reduced relative frequency of KR) could also enhance the learning of *classes* of actions, represented by generalized motor programs.

In the first experiment, we showed that systematically reducing the relative frequency of KR from 83% early in practice to 50% at the end of practice (with the average being 67%)—equally spread across three task versions with the same relative timing but different overall durations—tended to depress performance in the acquisition phase; however, when a *novel* variant of the same movement class was to be performed in the no-KR transfer test, the reduced relative frequency of KR produced clearly more effective relative timing performance than 100% KR.

In the second experiment, we contrasted the same amounts of KR as in the first experiment (i.e., 100% vs. 67%) but used an extreme KR manipulation, so that the no-KR group received 100% KR on two out of three task versions and 0% KR on the third (criterion) version, whereas the KR group received 100% KR on all three versions. The no-KR group's acquisition performance on the task version without KR was slightly impaired, as compared both with their performance on the other two versions and as compared with the KR group's performance on all three versions. However, the no-KR group clearly improved on this version over the course of acquisition—without *ever* receiving KR about it. This result implies that subjects generalized their experience on the two KR versions receiving KR to reduce their errors on the no-KR version.

Moreover, on the retention test (without KR), using the task version on which the no-KR group had 0% KR and the KR group had 100% KR during acquisition, the no-KR group demonstrated clearly more effective relative-timing performance. These results suggest that the no-KR subjects developed a more effective generalized motor program and that the reduced relative frequency during the acquisition phase facilitated this process. In this view, it would not particularly matter which versions actually experienced lowered relative frequency in acquisition—only that the relative frequency of KR for the *collection* of tasks experienced there was reduced. In this sense, Experiment 1 (where the relative frequency of all versions was decreased equally) and Experiment 2 (where the relative frequency for only one of the versions was reduced, but to 0%) both provide converging evidence for this view.

In some sense, the findings we have generated for KR seem parallel with those in the animal conditioning work. There, partial and faded reinforcement has been shown to slow acquisition but also to produce a slower decrease in the response rate during extinction (i.e., no reinforcement), the latter being analogous to a no-KR retention phase. One major hypothesis in the reinforcement work is that partial or faded reinforcement is effective because it tends to simulate the extinction conditions (e.g., Tarpy, 1982, chapter 7). One set of findings that argues against this similarity view, however, is that the effects of reduced relative frequency of KR are not specific to the KR condition on the retention test but manifest themselves not only on no-KR retention tests but also on 100% KR retention tests (Winstein & Schmidt, 1988); an analogous result would seem unlikely in the animal work. Additional evidence for different feedback functions in human and animal learning comes from findings on instantaneous feedback. In animal work, giving reinforcement quickly generally aids performance and learning, whereas instantaneous KR has been shown to degrade learning (Brackbill, 1964; Swinnen, Schmidt, Nicholson, & Shapiro, 1988). Instantaneous KR may interfere with the extra information processing activities in humans (e.g., attention to response-produced feedback) that are not present in animal subjects and thus lead to the differences in findings. Overall, while on the surface our findings with variations of KR scheduling appear to be similar to analogous findings in animal reinforcement work, there are too many instances where the feedback does not operate in the same ways for us to take this parallel very seriously.

A more viable explanation for the functioning of KR in human learning seems to be the guidance hypothesis for KR (Salmoni et al., 1984). According to this view, KR in practice provides several effects, one of which is a guidancelike process that drives the behavior toward the goal. Although this process is certainly beneficial and essential for learning, these guidance processes can generate an overreliance on KR that prevents the subject from engaging in various information-processing activities that would provide effective capabilities when KR is withdrawn and/or when the performance is required in a retention test. Thus, according to this view, relative to 100% KR conditions, various KR manipulations (such as the reduced relative frequency of KR examined here) that make KR "difficult" to use in acquisition will not produce effective performance there but will generate more effective performance in various transfer and retention tests. The fading procedure used in Experiment 1 should be useful, according to this view, because guidance is presented early in practice when it is most needed to bring the behavior onto target, but then KR is gradually withdrawn in later practice to prevent an overreliance on it. Of course, it is not clear from the present experiments as to which processes might be facilitated by the reduction of KR in acquisition. One possibility that has been considered (Schmidt et al., 1987, in press) is the learning of error-detection capabilities, where KR after every trial might block the learner's processing of response-produced feedback, and reduced KR frequency might generate increased awareness of it. In the present experiments, reduced KR might additionally focus the subject on the common features among the three tasks to be learned, facilitating the acquisition of the temporal structure inherent in the generalized motor program.

Overall, we have provided evidence that the principles of reduced KR frequency and faded KR—found earlier in single actions of various kinds (Winstein, 1988)—can be generalized to the learning of classes of actions, presumably those governed by generalized motor programs. Discovering the mechanisms associated with these effects will be an important task for the future if the underlying processes in KR utilization are to be understood. But whatever the exact processes underlying these results, these findings generate considerable difficulty for the long-held belief that more frequent and more "useful" information feedback is always more effective for learning, and they suggest that careful KR scheduling is critical if optimal task learning is the goal.

References

Adams, J. A. (1971). A closed-loop theory of motor learning. *Journal of Motor Behavior, 3,* 111–150.

Bilodeau, E. A., & Bilodeau, I. M. (1961). Motor skills learning. *Annual Review of Psychology, 12,* 243–280.

Bilodeau, E. A., Bilodeau, I. M., & Schumsky, D. A. (1959). Some effects of introducing and withdrawing knowledge of results early and late in practice. *Journal of Experimental Psychology, 58,* 142–144.

Brackbill, Y. (1964). The impairment of learning under immediate reinforcement. *Journal of Experimental Child Psychology, 1,* 199–207.

Heuer, H., & Schmidt, R. A. (1988). Transfer of learning among motor patterns with different relative timing. *Journal of Experimental Psychology: Human Perception & Performance, 14,* 241–252.

Lavery, J. J. (1962). Retention of simple motor skills as a function of type of knowledge of results. *Canadian Journal of Psychology, 16,* 300–311.

Newell, K. M. (1976a). Knowledge of results and motor learning. *Exercise and Sport Sciences Reviews, 4,* 195–227.

Newell, K. M. (1976b). More on absolute error, etc. *Journal of Motor Behavior, 8,* 139–142.

Salmoni, A. W., Schmidt, R. A., & Walter, C. B. (1984). Knowledge of results and motor learning: A review and critical appraisal. *Psychological Bulletin, 95,* 355–386.

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 control and learning: A behavioral emphasis* (2nd ed.). Champaign, IL: Human Kinetics Press.

Schmidt, R. A., Shapiro, D. C., Winstein, C. J., Young, D. E., & Swinnen, S. (1987). *Feedback and motor skill training: Relative frequency and summary KR* (Tech. Rep. No. 1/87). Los Angeles: Motor Control Laboratory, UCLA.

Schmidt, R. A., Young, D. E., Swinnen, S., & Shapiro, D. C. (1989). Summary knowledge of results for skill acquisition: Support for the guidance hypothesis. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15,* 352–359.

Shapiro, D. C., & Schmidt, R. A. (1982). The schema theory: Recent evidence and developmental implications. In J. A. S. Kelso & J. E. Clark (Eds.), *The development of movement control and coordination* (pp. 113–149). New York: Wiley

Swinnen, S. (1987). *Knowledge of results delay and motor learning.* Unpublished doctoral dissertation, Catholic University, Leuven.

Swinnen, S., Schmidt, R. A., Nicholson, D. E., & Shapiro, D. C. (1988). *Information feedback for skill learning: The degrading effects of instantaneous KR.* Manuscript submitted for publication.

Tarpy, R. M. (1982). *Principles of animal learning and motivation.* Glenview, IL: Scott, Foresman and Company.

Thorndike, E. L. (1927). The law of effect. *American Journal of Psychology, 39,* 212–222.

Trowbridge, M. H., & Cason, H. (1932). An experimental study of Thorndike's theory of learning. *Journal of General Psychology, 7,* 245–260.

Winstein, C. J. (1988). *Relative frequency of information feedback in motor performance and learning.* Unpublished doctoral dissertation, University of California, Los Angeles.

Winstein, C. J., & Schmidt, R. A. (1988). *The effects of frequency of knowledge of results on skill acquisition.* Manuscript submitted for publication.

Young, D. E. (1988). *Knowledge of performance and motor learning.* Unpublished doctoral dissertation, University of California, Los Angeles.

Received June 13, 1988
Revision received September 29, 1988
Accepted November 1, 1988 ■