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Reduced Frequency of Knowledge of Results Enhances Motor Skill Learning

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Relative frequency of knowledge of results (KR) is the proportion of KR presentations to the total number of practice trials. Contrary to predictions from most traditional motor learning perspectives (e.g., Adams, 1971; Schmidt, 1975; Thorndike, 1927), recent evidence suggests that, compared with practice in 100% relative frequency conditions, practice with lower relative frequencies may be beneficial to longer-term retention and learning, but detrimental to practice performance. Three experiments are reported in which the effects of variations in acquisition KR relative frequency were examined. Experiment 1 showed that a markedly reduced KR relative frequency during practice was as effective for learning as measured by various retention tests, compared with a 100% KR practice condition. In Experiments 2 and 3, when the scheduling of KR was manipulated so that the number of KR trials was systematically lowered across practice, a reduced average relative frequency enhanced learning as measured by a delayed no-KR retention test (Experiment 2) and a retention test in which KR was provided (Experiment 3). Results are inconsistent with predictions from an acquisition-test specificity hypothesis and conventional motor learning theories and thus suggest a revision in the principles governing the role of KR for motor learning. Empirical support is provided for the KR guidance hypothesis (Salmoni, Schmidt, & Walter, 1984) and for various encoding-retrieval operations associated with spaced retrieval practice. Possible learning strategies invoked by relative frequency and other related practice variations are discussed with respect to response consistency and the development of intrinsic error detection mechanisms.

In the field of motor behavior a considerable research effort has been directed toward understanding the principles governing the acquisition of motor skills (see Adams, 1987, for a recent review). Certainly, one of the most critical variables affecting motor skill learning, aside from practice itself, is feedback (Bilodeau & Bilodeau, 1961; Newell, 1976; Schmidt, 1988). One form of such feedback, termed *knowledge of results* (KR), has been the focus of a large body of research (see Salmoni, Schmidt, & Walter, 1984, for a review), and provides a fundamental cornerstone for motor learning theories (e.g., Adams, 1971; Schmidt, 1975). KR refers to the extrinsic information about task success provided to the performer after a practice trial has been completed. It is considered a subset of feedback, which is augmented, verbal (or verbalizable), postresponse information about the movement outcome in terms of the environmental goal. This information serves as a basis for error corrections on the next trial and as such can lead to more effective performance as practice continues. Because of the importance of feedback and KR, substantial work has been conducted in which the effects of feedback variations such as precision, delay, and frequency have been studied. We focus here on the frequency and scheduling of KR for motor skill learning.

Two primary descriptors related to the frequency of KR have been distinguished—absolute and relative frequency. Absolute frequency is the total number of KR presentations in a given practice session. Relative frequency is a ratio, expressed as a percentage, of the number of KR presentations to the total number of practice trials. It is well known that absolute frequency is an important variable for learning (e.g., Bilodeau, Bilodeau, & Schumsky, 1959; Newell, 1974; Trowbridge & Cason, 1932), but the effects of relative frequency are not well understood. In the most influential study, Bilodeau and Bilodeau (1958), using a simple lever-pulling task, examined four different relative frequency conditions. Blindfolded subjects pulled a vertically extended hand lever to a goal position. KR about the amount and direction of position error was provided as 10%, 25%, 33%, or 100% of the trials. KR absolute frequency was held constant between groups at 10 trials, and the distribution of these KR trials was uniform across practice. Thus, the relative frequencies were varied by

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allowing the number of interspersed no-KR trials to vary across relative-frequency conditions. Comparison of the four groups on the trials following each KR presentation (i.e., KR + trial) revealed no differences due to relative frequency. This suggested that the no-KR trials interpolated between the KR presentations were not particularly useful, as any number of them, from 0 (100% condition) to 9 (10% condition), did not seem to affect performance. Bilodeau and Bilodeau (1958) concluded that "learning is related to the absolute frequency, and not to the relative frequency of KR..." (p. 382).

Although generally consistent with other work (e.g., Bilodeau et al., 1959; Trowbridge & Cason, 1932), this interpretation failed to consider the important distinction between performance and learning, long known to learning psychologists (e.g., Guthrie, 1952; Tolman, 1932). Learning is defined by most behavioral researchers as a relatively permanent change in the underlying capability for responding. Given that KR is an important variable affecting *both* performance (e.g., Arps, 1920) and learning, it becomes necessary to separate temporary performance changes (e.g., motivational, informational) from those relatively permanent changes associated with longer-term retention and learning (see Salmoni et al., 1984, for further discussion of the performance vs. learning distinction in KR research). Experimentally, the transfer design is a common technique used to obtain a measure of these relatively permanent effects (e.g., Lavery, 1962). The Bilodeau and Bilodeau (1958) study mentioned earlier had not employed a transfer or retention test, and hence we argue that this experiment is mute with respect to learning.

The motor-learning literature is remarkably consistent in showing that during the practice phase with most simple laboratory tasks, nearly any variation that increases the amount, precision, or frequency of information feedback benefits performance and increases the rate of improvement over trials (see Newell, 1976; Salmoni et al., 1984, for reviews). From this it is easy to be led to the view that increased levels of feedback during practice would benefit learning. However, recent evidence from several different paradigms showed that although more frequent KR improved practice performance, it was less effective for performance in a retention test in which KR was withdrawn (Schmidt, Young, Swinnen, & Shapiro, 1989; Sherwood, 1988; Wulf & Schmidt, 1989; Young, 1988). In addition, several KR relative frequency experiments in which the learning–performance distinction was not ignored demonstrated similar performance and in some cases superior performance on a no-KR retention test for groups having practiced in low KR-relative-frequency conditions (Ho & Shea, 1978; Johnson, Wicks, & Ben-Sira, 1981).

The evidence cited above, though inconsistent with traditional views regarding the role of KR in motor learning, supports the recently proposed guidance hypothesis by Salmoni et al. (1984) which suggests that the use of KR may have both beneficial and detrimental effects. The beneficial effects concern the well-known informational contribution of KR that enhances goal attainment. The detrimental effects involve a kind of dependence that the learner develops with respect to the feedback. This guidance hypothesis emphasizes the learning–performance distinction, arguing that degraded performance during acquisition from certain KR variations (e.g., low relative frequency) may not reflect decrements in the relatively permanent capability for responding. In contrast to previous writers (e.g., Annett, 1969; Holding, 1965), Salmoni et al. (1984) have proposed that although frequent KR guides the subject toward the correct response, it may also lead to a dependency on the extrinsic feedback, which *prevents* the processing of other sources of information intrinsic to the task.

A more general phenomenon, primarily linked to verbal learning, may have theoretical relevance to the KR relative frequency findings. Specifically, the well-known lag or spaced-repetition effect originally described by Melton (1967) and later modified by Landauer and Bjork (1978) directly addresses the repetition frequency during practice of to-be-remembered items, showing beneficial effects on retention of spaced over massed practice. Other experiments using a presentation-test trial design with a motor memory paradigm provide insight into potential processing operations underlying KR frequency effects. A presentation trial either presents or provides an opportunity for the subject to produce the correct response. In this way, it is similar to a trial preceded by KR, in that a prescription for a correct response is provided. On the other hand, a test trial provides an opportunity for free recall of the desired response. It is similar to a trial not preceded by KR in that a correct response must be generated without an extrinsic cue or prescription. These presentation-test trial experiments showed that, during practice, spaced presentation trials following a series of test trials enhanced retention performance (and degraded acquisition performance) compared with a regime of serial presentation trials followed by a single test trial (Hagman [1983]; see also Izawa [1970], Lachman & Laughery [1968], and Thompson, Wenger, & Bartling [1980] for similar work in verbal learning). Together, the spaced repetition and test trial work suggests that intermittent KR presentations during practice (i.e., low KR relative frequencies) would be more beneficial for retention than would massed KR (i.e., high KR relative frequencies).

Although contrary to conventional motor learning views (e.g., Adams, 1971; Schmidt, 1975), several diverse yet convergent perspectives (i.e., KR-guidance, spaced repetitions, test trials) predict that above a certain minimum amount of KR, lowering the relative frequency should be beneficial to learning as measured by performance in a transfer or retention test. This prediction has some empirical support noted above (e.g., Ho & Shea, 1978; Johnson et al., 1981); however, results from these and others are inconclusive because KR relative frequency and the total number of practice trials were confounded (cf. Baird & Hughes, 1962; Bilodeau & Bilodeau, 1958; Bourne, Guy, & Wadsworth, 1967; Taylor & Noble, 1962) by holding KR absolute frequency constant. This procedure seemed natural at the time because of the importance given to KR presentations and the relative unimportance attributed to no-KR trials (cf. Bilodeau et al., 1959; Newell, 1974). However, by confounding KR relative frequency with practice trials, the low-relative-frequency groups had more total practice attempts than the high-relative-frequency groups. Therefore, one could propose the somewhat uninteresting hypothesis that merely practice itself, rather than a low relative frequency, determined superior performance.

Not all KR relative frequency studies confounded practice and relative frequency, however. Six separate experiments were performed, in which the amount of practice was held constant among acquisition groups, but the number of KR trials was varied (Annett, 1959; Set 2, Experiment 1; Goldstein & Rittenhouse, 1954, Experiments 1 and 2; McGuigan, 1959; Ho & Shea, 1978, Experiment 2; Schmidt & Shapiro, 1986, Experiment 1A; Schmidt, Shapiro, Winstein, Young, & Swinnen, 1987, Experiment 5). In all six of these studies a reduced KR relative frequency produced neither beneficial nor detrimental effects on learning, as measured by performance on a no-KR retention test. However, this design allowed KR absolute frequency to covary with KR relative frequency. As such, these findings are problematic for most conventional motor learning perspectives, which argue that a reduced absolute frequency of KR should be detrimental to learning (e.g., Adams, 1971; Bilodeau et al., 1959; Newell, 1974; Schmidt, 1975). In contrast, the KR guidance hypothesis, and the effects of spaced repetitions and test-trials previously discussed, predict superior performance from practice in low KR-relative-frequency conditions.

One general difficulty with previous KR relative frequency research is the relatively simple movement tasks used (e.g., line drawing, linear positioning) and the observation that acquisition performance usually reached an asymptote after only minimal practice (e.g., Ho & Shea, 1978). It may be that enhanced learning cannot be demonstrated with such simple tasks, and it raises doubt as to whether results from experiments such as these can be generalized. Therefore, the present experiments used a more complex motor task to test the prediction provided by several diverse yet convergent theoretical perspectives that practice with a reduced KR relative frequency, compared with a 100% condition (total trials held constant), would enhance motor skill learning as measured by retention test performance.

Experiment 1

In this experiment, there were two KR relative frequency acquisition conditions, 100% and 33%, with total trials held constant (absolute frequency allowed to covary). All previous KR relative frequency experiments for which retention performance was examined used no-KR retention tests. Thus, the evidence for beneficial learning effects attributed to a reduced KR relative frequency could be interpreted as simply an artifact resulting from the similarity between the conditions in acquisition and retention. With this notion, the acquired capability for responding would be specific to the particular retention test employed and would not represent a more generalized form of learning. Hereinafter, this view is referred to as the *specificity* hypothesis. In Experiment 1, to examine the specificity hypothesis more directly, four retention test conditions were used, each with a different KR relative frequency (i.e., 0%, 33%, 66%, and 100%). This 2 (acquisition condition) × 4 (retention condition) design resulted in eight separate acquisition–retention test groups.

Method

Subjects

Undergraduate students (74 female and 62 male) from the University of California, Los Angeles, Department of Kinesiology, participated in this experiment for course credit. Subjects were quasi-randomly assigned to one of eight groups, with constraints that group size ($n = 17$) and the female-to-male ratio between groups be equated. Subjects had no prior exposure to the experimental apparatus and were not aware of the specific purposes of the study.

Apparatus and Task

The experimental apparatus consisted of a lightweight aluminum lever affixed to a virtually frictionless vertical axle. The axle was mounted in specialized ball-bearing blocks which were anchored to a table. A handgrip was attached to the end of the lever opposite to the axle mount, and a foam pad covered the lever arm. An analog potentiometer was situated beneath the axle in such a way that horizontal lever movement was converted into a proportional signal. A plywood cover rested on the table to prevent visual monitoring of lever position from above. A graphics monochrome video monitor (VT 105) positioned in front of the table was used for the feedback display, with a shield to cover the screen on trials for which KR was not provided. Two small colored lights mounted on the table cover were used as trial warning and start signals.

While seated at the table, the subject grasped the lever handle with the right hand and rested the forearm on the foam pad. The task required the subject to produce a goal movement pattern. Subjects began the movement from 0° of lever rotation (approximately 100° of elbow flexion) with the lever and forearm in the subject's frontal plane. The goal movement pattern was represented by a temporal–spatial function consisting of four movement segments (i.e., three elbow extension–flexion reversals) produced in 800 ms. The timing and spatial characteristics of each segment were chosen so that the entire movement could not be produced simply by repetition of the first extension–flexion movement. The task required learning the precise temporal and spatial characteristics of the reversal points and the intervening movement trajectories.

Augmented feedback in the form of KR could be provided on the computer terminal after the movement attempt by superimposing the subject's temporal–spatial function with that of the goal movement. A variant of KR termed knowledge of performance (KP) provides information about the pattern of movement used to produce a response. The graphic feedback display used here represented the movement pattern and thus could be termed KP; however, the movement goal was isomorphic with the movement pattern and as such was considered a form of KR. The goal pattern appeared instantly following the response, and then the subject's displacement trace was superimposed with the same timing as in the original movement. For all displayed trials, the subject's trajectory was extended 200 ms beyond the 800-ms goal trajectory, thereby allowing the subject to more easily distinguish the two traces on the display. In addition, the root-mean-squared (RMS) deviation from the goal pattern was displayed, calculated from movement onset over the first 800 ms of the subject's trajectory. Figure 1 shows the kind of KR provided after a movement attempt.

All data were collected with a DEC 11/23 computer located in a room adjacent to the experimental room. A small microswitch, wired in parallel with the trial start light, was used as a Schmitt trigger to initiate a 2-s on-line sampling sweep for each trial. Analog potentiometer signals were digitized and sampled at 100 Hz. Of the 2 s of trial data collected, 1 s (i.e., 100 sampled points) was stored along with RMS error scores for later analyses.

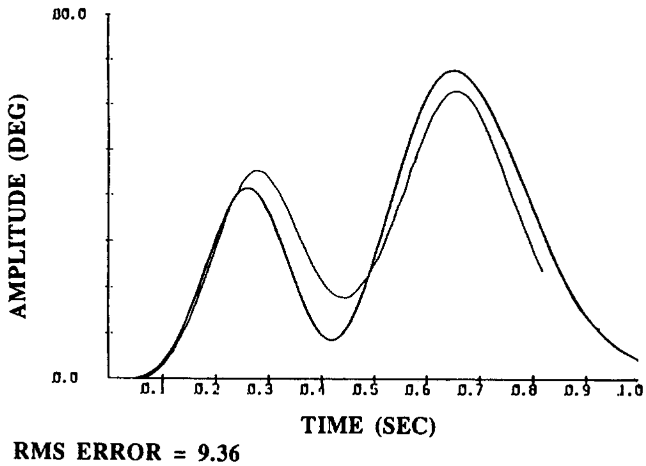

Figure 1. The goal movement pattern superimposed with a sample-trial movement pattern from 1 subject, showing the nature of the computer-produced feedback for a KR trial. (For trace differentiation, the goal pattern is 800 ms in duration, and the subject's trace extends for 1 s. The root-mean-squared [RMS] error was computed over the interval from 0 ms to 800 ms and is shown below the two trajectories. KR = knowledge of results.)

Procedures

Initially, subjects were familiarized with the apparatus, goal movement, KR (i.e., RMS error score and response trace), and trial cue lights. They were instructed to return the lever to the start position before the warning light and to initiate their movement any time during the 2-s interval after the cue light appeared. Two practice trials using the goal movement pattern were given. Then, four example illustrations of feedback displays, printed on graph paper, were used to demonstrate various spatial and temporal errors. Subjects were asked to identify errors on each example plot and to suggest response corrections that would lower RMS error scores.

The acquisition phase consisted of two 30-min sessions. The first immediately followed the familiarization period, and the second session was held the following day. Each session was composed of 99 trials, and the intertrial interval for all trials regardless of KR condition varied between 15 s and 20 s. Subjects in the 100% frequency group received KR after each trial, whereas subjects in the 33% group received KR pseudorandomly after two out of every six trials, with no more than four consecutive trials without KR. The first and last trial in each 99-trial session was always a KR trial. A random 33% KR trial schedule was generated before each session, and thus no 2 subjects in this group received KR on exactly the same acquisition trials.

For subjects in the 33% group, the shield was positioned over the computer screen unless the trial was designated a KR trial. On KR trials, the cover was lifted between movement completion and subsequent KR display. Thus, the 33% subjects did not know prior to the movement attempt whether or not KR would be presented, whereas the 100% subjects always knew. Subjects in both acquisition conditions were informed that during the retention session on the second day, they might not have KR displayed after each trial.

Following the second day of practice, subjects were asked to leave the experimental room and return after 10 min. A retention test of 27 trials then followed. KR was provided on zero, one, two, or three out of every three trials for subjects in the 0%, 33%, 66%, and 100% retention test conditions, respectively.

Results

Consistent with the performance–learning distinction for KR (Salmoni et al., 1984), separate analyses of acquisition and retention data were performed. The relative performance level during the acquisition phase is thought to represent a combination of the relative amount learned and the temporary effects of the KR variable being manipulated. In contrast, performance levels obtained during the retention phase are thought to reflect the relative amount learned (during the acquisition phase), in that the temporary effects of the KR manipulation are assumed to be controlled for each retention test condition. Thus, comparisons between levels of performance during acquisition and retention are not formally considered because they confound learning and performance effects (see Schmidt, 1988, for further discussion).

Performances in acquisition and retention were grouped into blocks of nine trials, where the primary dependent measure was RMS error. Secondary analyses were performed by using several kinematic measures of spatial and temporal accuracy at the three reversal points. These analyses were generally redundant with the RMS error scores but provided some additional insight into response consistency which is further discussed in the General Discussion. (See Winstein, 1988, for details of these kinematic analyses). Post hoc comparisons of means were conducted on significant analysis of variance (ANOVA) effects by using the Scheffé procedure when indicated.

Acquisition Phase

The group block means for the acquisition phase are summarized in Figure 2 for RMS errors on Day 1 (Blocks 1–11) and Day 2 (Blocks 12–22). Overall, for both groups, mean RMS errors decreased continuously about 7 RMS units, from $M = 14.6$ ($SD = \pm\ 3.91$) at the beginning of practice to $M = 7.2$ ($SD = \pm\ 1.73$) at the end of the second practice session (see Figure 2). Two separate ANOVAS, one for each session, revealed significant trial block main effects; Wilk's exact

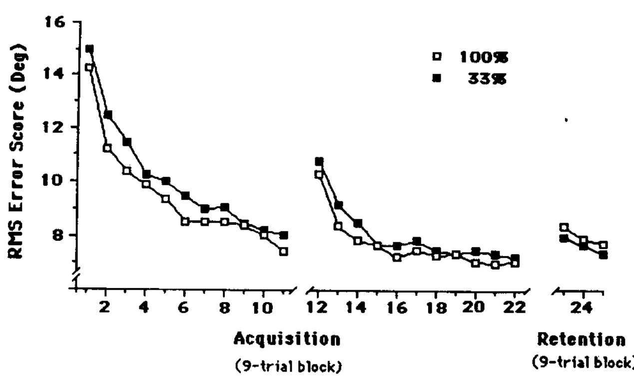

Figure 2. Average root-mean-squared (RMS) error for the two acquisition KR-relative-frequency conditions for Day 1 (Blocks 1–11), Day 2 (Blocks 12–22), and the retention phase (Blocks 23–25) in Experiment 1. (The retention data are collapsed across the four retention test relative-frequency conditions. KR = knowledge of results.)

Fs(10, 125) = 42.50 and 23.78, *ps* < .01, for the first and second day, respectively. In contrast to acquisition curves characteristic of "simpler" tasks (e.g., linear positioning), in which performance asymptotes are usually reached after a few practice trials, considerable practice was necessary here before performance stabilized.

Given the reduced KR frequency, it was not surprising that the 33% group demonstrated a tendency for larger errors than did the 100% group, particularly early in practice, which was consistent with several earlier findings (e.g., Bilodeau & Bilodeau, 1958; Johnson et al., 1981). However, the main effect for acquisition group was not statistically reliable for Session 1, $F(1, 134) = 2.91$, $MS_e = 49.91$, or Session 2, $F(1, 134) = 2.16$, $MS_e = 19.84$, $ps > .05$. These results suggest that the provision of less frequent KR may not be as detrimental to the acquisition process as previously thought.

Retention Phase

The four retention test condition RMS scores, averaged across subjects within the two acquisition groups, are presented in Table 1, along with across-subject standard deviations. Neither a reliable Block × Acquisition Condition interaction nor a Block × Retention Condition interaction was obtained. There was a tendency for the 0% retention condition to exhibit less improvement across retention blocks than the other three conditions, but this interaction was not reliable, $F(6, 256) = 1.87$, $MS_e = 2.00$, $p > .05$. Thus, for presentation in Table 1, the eight Acquisition × Retention condition means were averaged across the three retention test blocks.

Effect of retention-test condition. Both acquisition groups demonstrated the largest RMS errors in the 0% KR condition (8.8 RMS units), which represented about a 1.6-RMS unit increase from that at the end of the acquisition session. The RMS errors for the other three retention conditions were similar to each other but somewhat smaller than for the 0% condition, indicating that a condition with even a small amount of KR was more effective than a condition without KR; but increasing the amount of KR did not produce further performance gains. A 2 (acquisition condition) × 4 (retention condition) × 3 (block) ANOVA with repeated measures on the last factor revealed a significant retention condition effect, $F(3, 128) = 10.19$, $MS_e = 6.99$, $p < .01$. The post hoc analysis indicated that the error score for the 0% condition was significantly higher than that for any of the other three retention-test conditions, which were not different from each other. This generally supports previous findings showing that KR is a powerful performance variable, with higher KR relative frequencies providing more effective performance than conditions without KR.

Effect of acquisition conditions. As Table 1 shows, the 33% group tended to perform on average more accurately in retention than the 100% group (M = 7.62 vs. 8.05), but this effect was not significant, $F(1, 128) = 1.63$, $MS_e = 6.99$, $p > .05$. Thus there were no differences in learning, as measured by performance across several different retention tests, between groups having practiced under the two KR relative frequency conditions.

An acquisition–retention test specificity effect would be manifested as an interaction between the acquisition relative-frequency conditions and those of the retention test. As Table 1 indicates, there was a tendency for the 33% acquisition group to perform with slightly less error than the 100% acquisition group for each of the four retention conditions. Further, the Acquisition Condition × Retention Condition interaction was not statistically reliable. This provides no support for the specificity view of KR relative frequency effects. Therefore, the retention test conditions have been averaged together for display in Figure 2, where Blocks 23–25 are the three retention-test trial blocks. Performance for both acquisition conditions generally improved over the retention-test blocks, $F(2, 256) = 5.99$, $MS_e = 2.00$, $p < .05$. The 33% group tended to perform more effectively than the 100% group across all three retention blocks, but this effect was not significant. Thus, there was only minimal evidence that the variations in relative frequency used during the acquisition phase influenced the learning of this task, as measured by the retention-test conditions examined here.

Discussion

Experiment 1 produced no significant effects from variations in KR relative frequency on the learning of a coordinated movement pattern, as measured by the retention tests given after a 10-min retention interval. However, several interesting trends were revealed which provided a basis for further experimentation with this paradigm. First, the acquisition–retention condition interaction predicted by a specificity view was not supported by these findings. Rather, the 33% condition was uniformly slightly more accurate in retention, regardless of the relative frequency conditions. These findings

Table 1
Mean RMS Error Scores by Acquisition Group for Retention

	Retention relative frequency									
	0		33		66		100		*M*	
Acquisition relative frequency	*RMS*	*SD*	*RMS*	*SD*	*RMS*	*SD*	*RMS*	*SD*	*RMS*	*SD*
33%	8.51	1.95	7.54	1.29	6.92	0.82	7.50	0.93	7.62	1.25
100%	9.16	2.23	7.79	1.86	7.67	2.11	7.57	1.69	8.05	1.97
M across groups	8.83	2.09	7.66	1.58	7.30	1.47	7.54	1.31	7.83	1.61

Note. RMS = root mean squared. Units are in degrees. Means are averaged across Blocks 23–25.

run counter to a specificity view, in which those conditions in acquisition which most closely match those in retention should be the most effective for learning. Second, these findings imply that low KR-relative-frequency practice conditions may not be detrimental to learning as predicted by conventional motor learning views (e.g., Adams, 1971). The present findings provide no evidence for this and, indeed, provide weak evidence to the contrary. The results from Experiment 1, together with those from numerous other KR relative frequency studies, using various tasks (Annett, 1959, Set 2, Experiment 1; Ho & Shea, 1978, Experiment 2; McGuigan, 1959; Schmidt & Shapiro, 1986, Experiment 1A; Schmidt et al., 1987, Experiment 5), showed essentially no effects on learning, as measured by performance on both no-KR and KR retention tests. Thus, substantial evidence from studies in which KR relative frequency was manipulated while KR absolute frequency was allowed to vary contradicts conventional motor learning views that practice with fewer KR presentations would degrade learning. An interesting question concerns how these conditions with as little as one fifth the amount of feedback (Schmidt et al., 1987, Experiment 5) could contribute to the learning of this task as effectively as a condition with 100% KR.

Experiment 2

The guidance hypothesis of KR predicts that error information should be most useful early in practice to drive the performer toward the goal response. However, later in practice, when the response can be made more easily with less guidance, providing less frequent KR would not be particularly detrimental to the learning process; it might even be beneficial if it prevents reliance on the KR (Salmoni et al., 1984). An interesting parallel that may be useful for understanding the potential benefits from less frequent feedback can be derived from work involving spaced practice tests mentioned earlier (Landauer & Bjork, 1978) and the more general concept of retrieval practice developed by Bjork (1975, 1988). Using a name-learning task, Landauer and Bjork (1978) showed that to optimize the long-term retention effects of recall tests, an expanding sequence of intervals between tests of the to-be-remembered items (i.e., names) was better than a schedule with uniform intertest intervals. The expanded spacing of these practice tests maximized the probability for a *successful* execution in earlier tests, which in turn benefited later retrieval performance.

On the basis of the aforementioned spaced-practice test effects from verbal learning, and the predictions from the KR guidance hypothesis, the schedule of feedback trials for Experiment 2 was manipulated to enhance the effectiveness of a reduced KR relative frequency. With only one exception (Ho & Shea, 1978, Experiment 2), previous relative frequency research had used evenly distributed KR trial schedules. In contrast, for Experiment 2 here, KR was provided more frequently early in practice and was then gradually reduced later in practice. According to the guidance view, such a schedule should optimize the beneficial effects of KR by (a) directing the performer toward the target movement early in practice and (b) preventing dependence on the extrinsic feedback later in practice. Similarly, in accord with the spaced-practice test view, such a schedule should optimize retention performance by (a) providing for a successful execution at the time of the recall tests (i.e., no-KR trials) with more KR trials early in practice and (b) strengthening retrieval skills with fewer trials preceded by KR later in practice.

Method

Subjects

Undergraduate students (42 female and 16 male) from the University of California, Los Angeles, Kinesiology Department were quasi-randomly assigned to one of two relative-frequency groups in such a way that group size ($n = 29$) and the female-to-male ratio between groups were equated. Subjects were naive to the specific purposes of the study and had not previously used the experimental apparatus. Course credit was given for participation in the study.

Apparatus, Procedures, and Task

The apparatus, movement task, and procedures were the same as those described for Experiment 1, with a few exceptions outlined below. The shield that covered the screen during no-KR trials was eliminated through modification of the control software used during data collection. The CRT screen remained uncovered throughout the experiment, but for no-KR trials, only the target pattern was displayed after the movement attempt. Each of the two acquisition sessions was composed of 96 practice trials. The two treatment groups differed in the relative frequency of KR presentations during the acquisition phase. One group received KR following all practice trials (100% condition), while the other group (50% condition) received KR after half of the practice trials in each session. Following the acquisition phase, two 12-trial no-KR retention tests were administered; the first was 5 min after the end of the last practice session, and the second was approximately 24 hr later.

In contrast to Experiment 1, where the KR trials were evenly distributed throughout the practice phase, a variable-ratio schedule was employed in the 50% condition here. The proportion of KR trials on each practice day was relatively high early, but low toward the end of practice. Specifically, the first 22 trials of each day were preceded by KR. After this initial 100% phase, 8-trial no-KR blocks were introduced, separated by progressively shorter KR trial strings. The KR trial strings were successively 8, 7, 4, 3, 2, and 2 trials long, with these last 2 KR trials constituting the final trials for each practice session. In this way, the average relative frequency for the moderate relative frequency group was 50%, but the "local" relative frequency, computed across 8-trial blocks, was progressively reduced from 100% to 25% throughout practice. Because the total number of practice trials was held constant between acquisition groups, the KR absolute frequencies were 192 and 96 for the 100% and 50% conditions, respectively.

Results

Acquisition Phase

KR and no-KR trials together. Performance in acquisition was grouped into blocks of 12 trials; group RMS error means for the two sessions (Blocks 1–8 and 9–16, respectively) are summarized in Figure 3. Error reduction across practice

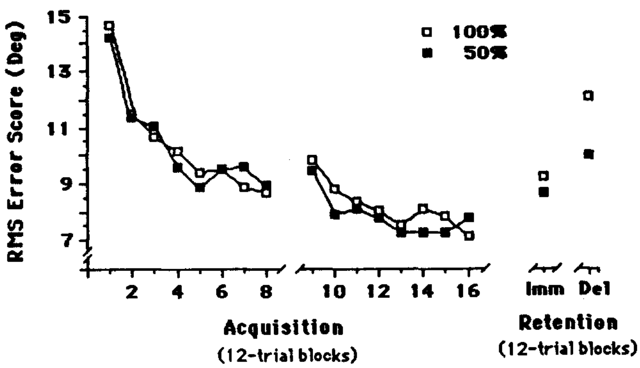

Figure 3. Average root-mean-squared (RMS) error for the two acquisition KR relative frequency conditions for Day 1 (Blocks 1–8), Day 2 (Blocks 9–16), immediate, and delayed no-KR retention tests in Experiment 2. (KR = knowledge of results.)

blocks was similar to that seen in Experiment 1. Generally for both groups, mean RMS errors dropped about 7 RMS units from $M = 14.4$ ($SD = \pm 4.34$) at the beginning of practice to $M = 7.4$ ($SD = \pm 1.98$) at the end of the second practice session. Two separate ANOVAS revealed a significant trial-block main effect for the first and second day, Wilks's exact $Fs(7, 50) = 13.2$ and 7.3, $ps < .05$, respectively. In contrast to Experiment 1, no group RMS error differences were evident early in the acquisition phase. This was not surprising, given that the KR-relative-frequency schedule for the first 22 trials (i.e., nearly two blocks) was identical for both groups. On the second practice day, there was a tendency for subjects in the 50% condition to have slightly lower RMS errors than those in the 100% condition, but these group effects were not significant for either day.

KR and no-KR trials separated. To facilitate the between-group comparison, trials for the 50% condition were collected separately into KR and no-KR trial blocks. For this blocking procedure, a KR trial was defined as one with KR preceding it, and a no-KR trial was one without KR preceding it. Thus, the first trial of a KR trial string was included in the previous no-KR trial block, and the first trial of a no-KR trial string was included in the previous KR trial block. In contrast to the blocking procedure used in Figure 3, in Figure 4 the KR and no-KR trials were blocked separately for the 50% condition, filled as indicated by the open and filled squares. The corresponding trials were then used to block performance trials in the 100% condition (crosses); but for this group, naturally, all blocks contain KR trials.

Across blocks, in contrast to the relatively smooth curves for the 100% condition, the 50% condition showed obvious performance fluctuations corresponding roughly to the alternation of KR and no-KR blocks (see open and filled squares). As expected, performance for the 50% condition generally improved with KR but deteriorated slightly without it. For the 50% group, the difference between performance with KR (open squares) and without KR (filled squares) in Figure 4 represents a measure of the temporary performance effects of KR (Salmoni et al., 1984). On the average, that difference was approximately 0.5 RMS units.

Similar to the Bilodeau and Bilodeau (1958) KR + 1 trial comparison, a between-group analysis was conducted with only the nine KR blocks for each acquisition session (open squares and corresponding crosses in Figure 4). On Day 1, no remarkable group differences were revealed. But on the second day of practice, subjects in the 50% relative frequency condition demonstrated significantly lower RMS errors than did subjects in the 100% condition, $F(1, 56) = 4.15$, $MS_e = 24.06$, $p < .05$. These findings are clearly inconsistent with those of Bilodeau and Bilodeau (1958) and those predicted from either a specificity of training perspective or conventional motor-learning viewpoints.

KR retention test. The three KR trial blocks at the beginning of the second day of practice, which were experienced by both groups, could be considered a delayed KR retention test of the relative amount learned on Day 1. Here, the temporary effects from the practice conditions on the first day of practice have been allowed to dissipate, and all subjects return on the second day to a retention test for which KR is provided. A specificity view would predict that subjects who practiced in a 100% KR-relative-frequency condition would perform more effectively on this KR retention test than would subjects who practiced in a 50% condition. On this test (Blocks 16–18, Figure 4), subjects who practiced with fewer KR presentations (i.e., 50% condition) exhibited lower RMS errors than did subjects who practiced under 100% KR conditions—opposite to the ordering predicted by a specificity view. However, in contrast to the group effect obtained earlier across all nine KR blocks for Day 2, the group effect here was not significant, $F(1, 56) = 2.73$, $MS_e = 11.59$, $p > .05$. Performance on KR retention tests is not routinely used as a measure of learning because the temporary guiding effects from the KR are usually so overpowering that any differences due to relatively permanent underlying capabilities are masked. But here, the RMS group mean differences observed initially on Block 16 (difference = 0.72 RMS units) seemed to persist and even to increase slightly (difference = 0.81, and

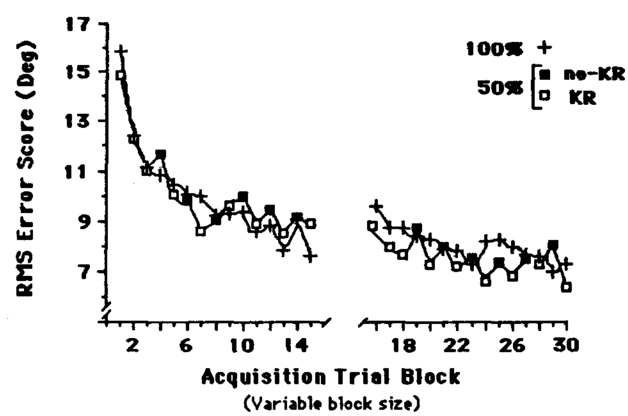

Figure 4. Average root-mean-squared (RMS) error for KR and no-KR blocks across the acquisition phase for the 50% KR-relative-frequency group in Experiment 2. (Trials were similarly blocked for the 100% group, but all blocks are composed of KR trials. Block size varies across the abscissa but is constant for any given block across groups. KR = knowledge of results.)

1.02 RMS units for Blocks 17 and 18, respectively) throughout the three KR blocks.

Retention Phase

No-KR retention tests. The group mean RMS scores are presented on the right side of Figure 3 for the immediate and delayed no-KR retention tests. In general, RMS scores for both groups increased from the end of practice to the immediate retention test, but performances of the 100% subjects deteriorated considerably more than did those of the 50% subjects—2.1 versus 0.9 RMS units, respectively. This same trend was observed 1 day later on the delayed retention test. The tendency for the 50% group to perform with less error than the 100% group on the 5-min no-KR retention test was not significant. However, on the delayed no-KR retention test (Figure 3), the 50% group demonstrated 35% less RMS error than the 100% group, and this difference was statistically reliable, $F(1, 56) = 6.24$, $MS_e = 10.25$, $p < .01$. Thus, compared with giving feedback on all trials, providing fewer KR trials in acquisition and distributing them with a systematic schedule of faded KR produced more accurate performance on a delayed no-KR retention test.

Discussion

Experiment 2 provides a number of new findings that have strong implications for theory. First, contrary to several conventional viewpoints (Adams, 1971; Bilodeau, 1969; Schmidt, 1975; Thorndike, 1927) which hold that providing less KR should degrade learning, the present experiment showed that fewer KR presentations during the practice phase actually improved learning, as measured by performance on a delayed no-KR retention test. This suggests that factors other than the number of KR presentations (i.e., KR absolute frequency) are operating here. Contrary to the earlier conclusions of Bilodeau and Bilodeau (1958), this experiment showed that KR relative frequency is indeed a relevant practice variable for learning. Of course, the Bilodeau and Bilodeau conclusion was based only on an analysis of performance during acquisition where both temporary and relatively permanent effects are present.

A Comparison With Bilodeau and Bilodeau (1958)

The performance difference for blocks with KR is inconsistent with that obtained earlier by Bilodeau and Bilodeau (1958). However, in their study, KR absolute frequency was held constant between the various KR relative frequency groups, and the total number of practice trials between groups was allowed to vary. If, as Bilodeau and Bilodeau suggested, KR absolute frequency rather than relative frequency is the important variable, then a between-groups comparison in the present experiment using only KR trials should show no effects from KR relative frequency. To examine this hypothesis, data from Experiment 2 were replotted in Figure 5, holding KR absolute frequency constant across groups.

For the 50% relative frequency condition, only the KR trial blocks were used, and the no-KR trials were discarded, leaving

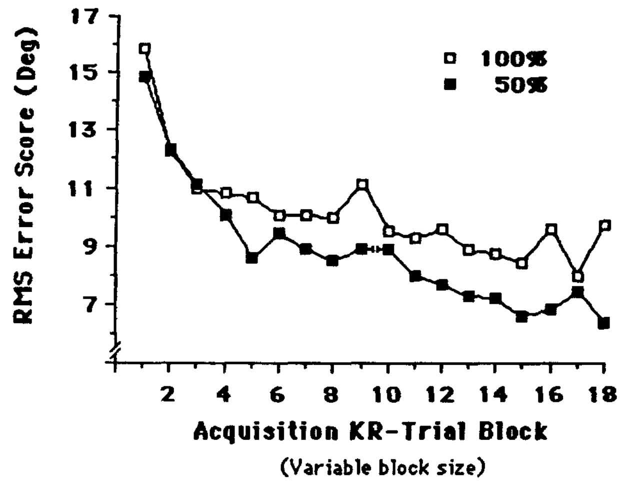

Figure 5. Average root-mean-squared (RMS) error for the two KR relative frequency groups for only KR trials in Experiment 2. (The break in the 50% curve corresponds to the interval between the 2 practice days. Block size varies across the abscissa but is constant for any given block across groups. KR = knowledge of results.)

18 KR blocks. Together the KR blocks represent 95 KR trials (absolute frequency), out of 192 total practice trials. An equivalent number of trials were blocked in the same manner for the 100% group, but no intervening trials were discarded. Trials after the 95th KR trial for the 100% subjects were not included in this analysis. Figure 5 represents a comparison across these KR trials, similar to the KR + 1 trial comparison used by Bilodeau and Bilodeau (1958, see their Figure 1). In contrast to their findings in which no group differences were evident, here, after the first three KR blocks, the 50% group demonstrated generally more effective performance than the 100% group, and this difference increased across practice. This overall acquisition-condition effect, $F(1, 56) = 5.88$, $MS_e = 82.88$, $p < .05$, suggests that KR relative frequency is a relevant performance (or learning) variable; further, the interpolated no-KR trials appear not to have been "blank" with respect to performance, but rather seem to have provided some beneficial effects. It is difficult to interpret this comparison, given the differences between the two studies, including (a) KR schedule, (b) amount of practice, (c) motor task, and (d) KR block versus trial comparison. But certainly the Bilodeau and Bilodeau conclusion that KR relative frequency is unimportant is not correct in general.

Enhanced Learning or Acquisition–Retention Test Similarity?

Experiment 2 demonstrated that fewer KR presentations enhanced learning as measured by performance on a delayed no-KR retention test. However, advocates of a specificity view might argue that the low-frequency condition more closely resembled the no-KR retention conditions; therefore, it would not be surprising that subjects who practiced under that condition performed best on this retention test. Although such an explanation cannot be ruled out definitively by Experiment 2, the KR retention test obtained from performance at the beginning of Day 2 provides some evidence against this specificity explanation. The specificity view predicts that subjects with 100% KR on Day 1 should demonstrate less error in a Day 2 KR retention test than subjects with 50% KR on Day 1. Contrary to this prediction, there was a (nonsignificant) tendency for the 50% KR-relative-frequency group to exhibit lower RMS errors than for the 100% group on this KR retention test. The implication is that the beneficial effects from practice conditions with moderately low KR relative frequencies are due to enhanced learning and are not due simply to the compatibility between acquisition and retention test conditions. An obvious test of this prediction would involve an experiment that provides formal transfer to a KR retention test, which was the motivation for Experiment 3.

Experiment 3

Experiment 3 was designed to examine more formally the possibility that the beneficial effects from the KR-relative-frequency schedule obtained in Experiment 2 were due simply to the similarity between the acquisition and retention-test conditions. The same KR and no-KR trial schedules used in Experiment 2 were used here for the acquisition phase, but a delayed retention test with KR was used as a measure of the relative amount learned.

Method

Subjects

Undergraduate students (26 female, 20 male) from the University of California, Los Angeles, Kinesiology Department were quasi-randomly assigned to one of the two relative frequency groups in such a way that the female-to-male ratio between groups was equal. Subjects were naive to the specific purposes of the study, and none had been a subject in any of the previous experiments. Course credit was given for participation.

Apparatus, Procedures, and Task

The experimental procedures, movement task, KR-relative-frequency conditions (100%, 50%), and KR trial schedule were the same as those used in Experiment 2, with the following exceptions. No immediate retention test was given. Instead of a delayed no-KR retention test, a 12-trial retention test with KR was administered 1 day after the second day of practice.

Results

Acquisition Phase

Performance in acquisition, grouped into blocks of 12 trials, is displayed in Figure 6 (Blocks 1–8 and 9–16, for Days 1 and 2, respectively). Error reduction across practice blocks, similar to that seen in Experiment 2 was approximately 7 RMS units over the 2-day practice period, and this trial-block main effect was significant for the first and second day, $Fs(7, 44) = 20.65$, $MS_e = 5.04$, and 13.21, $MS_e = 2.20$, $ps < .01$, respectively.

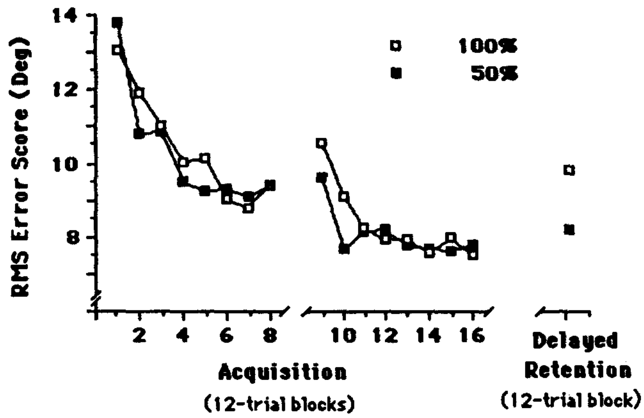

Figure 6. Average root-mean-squared (RMS) error for the two acquisition KR-relative-frequency conditions for Day 1 (Blocks 1–8), Day 2 (Blocks 9–16), and the delayed KR retention test in Experiment 3. (KR = knowledge of results.)

No group differences were evident early in the acquisition phase. But on the second practice day, there was a tendency for subjects in the 50% condition to have slightly lower RMS errors than those in the 100% condition. However, these acquisition-condition main effects were not significant.

The tendency for the 50% KR-relative-frequency group to perform more accurately on Day 2 was most evident early in practice (see Blocks 9–10 in Figure 6). Of particular interest here is the fact that the 50% group, having practiced with fewer KR presentations on Day 1, performed better under these altered 100% KR conditions in the first block of Day 2 than did the 100% group, which practiced with the identical conditions. These findings were reminiscent of Day 2 performance for the 50% group in Experiment 2. However, the acquisition-condition main effect for Block 9 was not statistically reliable, $F(1, 44) = 1.72$, $MS_e = 5.87$, $p > .05$.

Retention Phase

Group mean RMS scores are presented on the right side of Figure 6 for the delayed KR retention test. As expected, RMS scores for both groups increased from the end of practice to the retention test. There was a significantly lower RMS error for the 50% group compared with the 100% group, $F(1, 44) = 6.56$, $MS_e = 4.53$, $p < .02$. Thus, providing fewer KR presentations during practice produced more accurate performance on a delayed retention test with KR than that achieved by providing 100% KR during practice.

Discussion

The results of Experiment 3 extended those of Experiment 2 and provided further evidence to support the notion that practice with a reduced KR relative frequency is beneficial for skill learning. More important, these beneficial effects were obtained by using a delayed KR retention test as a measure of learning, thus providing strong evidence against the specificity hypothesis. These findings suggest that the KR practice schedule used in the 50% condition facilitated the development of a capability for responding that appeared to be relatively independent of the superficial similarity between the acquisition and retention test conditions.

General Discussion

Together, the present experiments support and extend earlier investigations of KR relative frequency is motor-skill learning. All three experiments unraveled the effects of amount of practice and relative frequency, which were confounded in a number of earlier studies allowing the effect of KR relative frequency to be examined separately from that attributed to practice. Of those earlier experiments which did hold the number of practice trials constant (e.g., Annett, 1959; Set 2, Experiment 1; McGuigan, 1959; Schmidt & Shapiro, 1986, Experiment 1A), the role of KR relative frequency was usually examined with tasks requiring control of only a single kinematic degree of freedom (e.g., line drawing, ballistic timing; but see Schmidt et al., 1987, Experiment 5 for the exception). Those experiments were extended with the present research to the learning of a relatively more complex coordinated action which required considerable practice before a performance plateau was evidenced.

In the present experiments, the covariation between absolute and relative frequency actually provides an interesting challenge to most motor learning perspectives which predict that enhanced learning is brought about by increasing the absolute frequency of information feedback. With these views, information feedback produces learning by guiding the performer to the goal behavior (Adams, 1971), by strengthening the bonds between the stimulus conditions and the target response (Thorndike, 1927), or by establishing memorial structures (e.g., schemas) which define input–output rules about limb control (Schmidt, 1975, 1976). Further, these views suggest that no-KR trials are either "neutral" for learning (Schmidt, 1975; Thorndike, 1927), or they degrade learning (Adams, 1971) by allowing the learner to drift from the correct response. In contrast, the present findings suggest that no-KR trials seem to neutralize the detrimental effects of fewer KR presentations (Experiment 1) and can even contribute to enhanced learning if they are systematically distributed throughout practice (Experiments 2 and 3). Our results, therefore run counter to predictions from these views, suggesting that a revision in the accounts of how feedback operates for motor learning is needed.

Specificity Hypothesis Not Supported

One relatively simple explanation for the results of Experiment 2—termed the *specificity hypothesis* (cf. Henry, 1968; Tulving & Thomson, 1973)—suggests that, for a given retention test condition, performance is maximized to the extent that the acquisition conditions are similar. Indeed, a specificity view predicts that a practice condition entirely without KR would most closely match a no-KR retention test and thus should be the best acquisition condition for such a test. Obviously, a certain minimal level of KR would be needed initially, and this prediction from the specificity view has not held in several earlier experiments (Bilodeau et al., 1959; Trowbridge & Cason, 1932).

In Experiment 1, a specificity view would have predicted an interaction between the relative-frequency conditions in acquisition and retention. No such interaction was shown. Rather, the 33% acquisition condition was slightly (though not statistically) more effective in retention than the 100% acquisition condition and across all four transfer relative frequencies. In Experiment 2, a specificity view predicts that the 100% acquisition condition would have been most effective for the Day 2 KR retention test. Although not statistically reliable, the 50% acquisition group performed with *less* RMS error than did the 100% group. Finally, in Experiment 3, a specificity view predicts more effective performance for the 100% acquisition condition on the delayed KR retention test. Instead, the 50% group, having practiced with fewer KR presentations, performed with 14% less error than the 100% group, which practiced in a condition identical to that of the retention test. These data suggest that although there may be some sense in which the similarity of acquisition and retention conditions is a factor in retention performance, it does not appear to be the major factor (Bransford, Franks, Morris, & Stein, 1979; Lee, 1988).

Possible Benefits From Intermittent Feedback Presentations

There are at least three independent, yet convergent, lines of research which provide support for the notion that a practice regime of intermittent feedback presentations would be better for retention than one with feedback massed throughout practice. The first of these, referred to earlier as the *guidance hypothesis*, suggests that KR has beneficial effects on performance and learning, but it also can have detrimental effects, primarily if the performer becomes dependent on its guiding properties. Second, the spaced-practice hypothesis based on evidence in verbal learning suggests that recall performance is enhanced when practice tests of to-be-remembered items are spaced rather than massed throughout practice. Finally, a viewpoint which we will refer to as the *consistency hypothesis* suggests that massed KR facilitates response variability which is detrimental to the establishment of stable performance. In contrast, intermittent KR presentations allow the development of response accuracy and consistency, both important components of skill learning. Potential mechanisms associated with these three hypotheses will be explored further in the next section.

Guidance hypothesis. Early research into the effectiveness of various types of feedback (e.g., continuous, terminal) focused primarily on the practical aspects of skill acquisition. In a number of these early studies and later reviews, researchers warned that if the subject was to eventually perform the practiced task without feedback, it was important to remove that feedback as part of the practice regime (Annett, 1969; Annett & Kay, 1957; Goldstein & Rittenhouse, 1954; Holding, 1965; Welford, 1976). Implicit in this caveat is the assumption that the performer may become dependent on the feedback, and this dependency will be detrimental to skill acquisition. This earlier dependency view was recently extended and formalized into the guidance hypothesis of KR (Salmoni et al., 1984; Schmidt et al., 1989).

The KR guidance hypothesis suggests that two opposing processes are associated with the role of feedback in motor learning. First, feedback has a beneficial effect in that it guides the learner toward the goal movement by providing information for error correction, and it tends to keep the learner motivated and interested in the task (Bilodeau, 1969). Second, similar to guidance, feedback also has a detrimental effect in that it allows the subject to continue to use its guiding and motivating properties to maintain performance and may even allow the learner to become dependent on it. According to the guidance view, this dependence may involve at least two distinct and separable processes. First, when feedback is always available during practice, it actually becomes part of the task, so that when it is withdrawn later in a retention test, part of the task is withdrawn with it and performance suffers (Proteau, 1987). This view is reminiscent of paired-associate verbal learning tasks in which strong stimulus–response associations resulting from response generation can ultimately be detrimental to later free recall of the generated response (e.g., Yekovich & Manelis, 1980). The second factor in feedback dependency deals with an interference in, or prevention of, other important task-related operations such as those involved in error-detection. When error information is supplied externally via KR, the subject may be less likely to process the inherent response-produced feedback associated with movement production. If such processing is prevented by the consistent provision of the more salient KR, formation of an effective memory representation of the to-be-learned action might suffer.

When KR relative frequency is implemented by using a uniform KR trial distribution, the detrimental effects associated with less error information may be neutralized by the beneficial effects attributed to less dependence on the KR. This provides an explanation for the results of Experiment 1 and a number of other experiments which showed no effect of KR relative frequency on learning. In Experiments 2 and 3, where the relative frequency schedule was manipulated in an attempt to optimize its effectiveness, the beneficial effects from the interpolated no-KR trials were shown to outweigh the detrimental effects from fewer KR presentations (see also Wulf & Schmidt, 1989).

Of course, another possibility could have been that the beneficial effects of a reduced KR relative frequency, regardless of the schedule, were obscured in Experiment 1 by not allowing a longer retention interval and/or by using a suboptimal practice relative frequency. An earlier experiment using the same movement task and five different uniformly distributed KR practice frequencies from 20% to 100% was conducted with both immediate (5 min) and delayed (2 day) no-KR retention tests (Schmidt et al., 1987, Experiment 5). The results from this experiment were consistent with those from Experiment 1 and with a relatively large range of KR relative frequency practice conditions. When those results are compared with the results of Experiment 2 in the present study, it suggests that the scheduling of KR is an important factor in optimizing the beneficial effects of intermittent KR presentations.

Recently, however, Nicholson and Schmidt (1989) replicated the results of Experiment 2 and extended them by comparing performance achieved in a 100% relative frequency condition with that of three different 50% relative frequency conditions. Two of the 50% conditions had uniformly distributed KR trials—one with alternating single KR and no-KR trials, and the other with alternating 5-trial KR and no-KR blocks. The third 50% condition used a faded KR schedule similar to that used in Experiments 2 and 3. They found no differences on a 24-hr, no-KR retention test among the three 50% groups, all of which performed with less error than the 100% group, suggesting that the beneficial effects of a reduced KR relative frequency were due to relative frequency alone, independent of scheduling. Given the inconsistent findings of these previous experiments, it is somewhat premature to conclude that KR scheduling is unimportant within the motor learning domain; further experimentation will be needed to resolve this issue. Within the verbal learning domain, several studies have shown that an expanded interval test-trial schedule produces superior retention performance when compared with a uniform interval test-trial schedule with the same average interval length (Landauer & Bjork, 1978, see discussion below). Analogous practice schedules with the use of KR may prove beneficial for motor skills as well.

Spaced-retrieval hypothesis. The second major theoretical view supported by the present findings comes primarily from research in verbal learning pertaining to the notion of retrieval practice (Bjork, 1975, 1988) as it relates to the scheduling of "tests" (or recall trials) during acquisition (e.g., Landauer & Bjork, 1978; see also Hagman, 1983, for similar work in motor skills). With respect to KR relative frequency, a practice trial not preceded by KR is similar to a free recall or retrieval episode in that a response must be generated without an external prescription. In this way, movement responses with the use of a faded KR schedule provide an opportunity for retrieval practice during no-KR trials and may benefit motor performance on a later retention test in a similar manner to that which operates for verbal learning (Landauer & Bjork, 1978) and other cognitive skills (Rea & Modigliani, 1985). In contrast, a trial preceded by KR may be similar to a presentation trial for which minimal, or at least different, retrieval processes are required. This comparison of test/presentation and no-KR/KR trials suggests a parallel between practice regimens in verbal learning in which spaced retrieval is used and motor learning in which KR relative frequency is used. In this regard, the processes involved in retrieval afforded by no-KR trials may be a form of transfer-appropriate processing (Bransford et al., 1979; Lee, 1988). It is in this sense in which a similarity between the conditions in practice and retention may be beneficial. The results of Experiment 3 suggest that the processes associated with the faded KR practice schedule are also beneficial for a KR retention test. Other recent work in motor learning has shown that the beneficial effects from a reduced KR relative frequency can be extended to the development of a more generalized capability for responding (Wulf & Schmidt, 1989).

Another verbal learning practice variation used primarily with paired associates and termed *percent occurrence of response members* (%ORM) provides some interesting parallels to the KR relative frequency work. In %ORM, subjects practice stimulus–response word pair lists, but the response member is presented with the stimulus member on only a proportion of the acquisition trials (Goss & Nodine, 1965). Most of the %ORM experiments used a trials-to-criterion method during acquisition. Thus, like the early KR relative frequency studies, %ORM was confounded with the number of practice trials. As expected, the conditions with low %ORM usually required more trials to criterion (e.g., Goss, Morgan, & Golin, 1959, Schulz & Runquist, 1960). For example, Schulz and Runquist (1960) used five levels of %ORM (i.e., 100%, 80%, 60%, 40%, and 20%) and a one-perfect-trial learning criterion. The number of trials to criterion did increase, but not substantially, with 17.5, 18.7, 16.8, 21.8, and 22.7 trials for the five conditions, respectively. Although trials-to-criterion and %ORM were confounded, it was relatively small. Of relevance, however, is that on an immediate 0%ORM retention test, there was essentially no effect of the acquisition %ORM with number of correct items being 6.4, 6.8, 6.6, 6.5, and 6.6 for the five conditions, respectively. These results are quite similar to those of the earlier KR relative frequency studies (e.g., Ho & Shea, 1978; Johnson et al., 1981). A particularly relevant study done by Krumboltz and Weisman (1962) used programmed instruction methods and a fixed number of acquisition trials across six different %ORM practice conditions. On an immediate 0%ORM retention test, there was almost no difference in items correct between the various conditions. This study is similar to Experiment 1 and numbers of previous KR relative frequency studies in which immediate retention tests were employed and practice trials were fixed.

In general, the %ORM work showed a lack of effect of a reduced %ORM on paired-associate learning—a result which the verbal learning researchers found surprising (e.g., Goss et al., 1959; Schulz & Runquist, 1960). Notwithstanding the limitations of these studies (i.e., trials were rarely fixed across %ORM conditions, and delayed retention tests were not used), the findings tended to agree with ours. This suggests that there may be some commonalities in these two paradigms.

Consistency hypothesis. It has long been known for a variety of tasks that during practice, as skill develops, performance becomes not only accurate but also more consistent across trials. In motor learning research, the most commonly used indicators of performance accuracy and consistency are constant error (CE) and variable error (VE), respectively. However, variable error is by far the most sensitive with respect to changes across practice. In this regard, studies investigating the effects of KR variations generally show that CE approaches zero within a few trials, but VE responds much more slowly. Earlier analyses of acquisition performance under various KR relative frequency conditions indicated that during periods of trials that were not preceded by KR or during conditions of low KR frequencies, more consistent performance was obtained (i.e., lower VE) compared with that during trials preceded by KR or conditions of high KR frequencies (Bilodeau & Jones, 1970; Ho & Shea, 1978, Experiment 2; Rubin, 1978). These findings suggest that when KR is available, the performer is more likely to adjust the response with each succeeding trial. In contrast, when learners are performing motor actions during strings of trials without KR, the opportunity to repeat a given action dominates, corrections are not extrinsically elicited, and performance tends to be more stable.

In Experiment 2, kinematic analyses of acquisition performance revealed that subjects who practiced in the 50% condition tended to have larger CEs but smaller VEs, particularly in timing, compared with subjects who practiced in the 100% KR condition. Additionally, in the no-KR delayed retention test, the 50% group demonstrated slightly smaller VEs and CEs compared with the 100% group, particularly with respect to spatial amplitudes (Winstein, 1988). Although not pronounced, these findings suggest that fewer KR presentations facilitate response consistency during practice to a greater extent than conditions in which KR is provided more frequently. This response consistency seems to have beneficial effects on learning as evidenced by retention test performance. Similarly, Sherwood (1988) used a KR variation known as *bandwidth-KR*, in which KR was provided only if the response error was outside some predetermined range that was expressed as a percentage of the goal movement time. He found lower VE scores in a no-KR retention test for subjects having practiced in a condition with a large bandwidth (i.e., fewer KR trials) than one in which KR was provided on every trial. Of course, in the bandwidth-KR condition, if KR is not provided after a movement attempt, the implicit instructions are to simply repeat the previous movement.

Thus, several sources, together with the present results, suggest that lower KR relative frequencies reduce variability from trial to trial. In contrast, high KR frequencies seem to facilitate response variability. There are at least two detrimental effects associated with this KR-induced variability. First, the subject does not have an opportunity to develop a stable action pattern because of the frequent changes elicited by the KR. These KR-induced changes, termed *maladaptive short-term corrections* (R. A. Bjork, personal communication, December 17, 1987), make performance more accurate in the short term but less stable for long-term learning. Such short-term performance gains may instill a false sense of performance capability. Second, KR-induced corrections which are superimposed on an unstable action pattern may not be particularly useful for updating response-production memory structures. In contrast, the KR-trial block analsyis of RMS conducted in Experiment 2, and previous work reported by Hagman (1983), suggests that the utilization of KR for error correction is enhanced or "potentiated" after some level of response consistency has been induced by a series of test trials or trials not preceded by KR.

There are at least two plausible explanations for the enhanced utilization of KR in the reduced-feedback condition. The first provides that response consistency (generated over several no-KR trials) is useful at the time of the subsequent KR presentation, whereupon adjustments in accuracy are more easily made to a stable response pattern. The second explanation concerns response accuracy and the salience of the intermittent KR. There is evidence for performance deterioration during no-KR trials (cf. Figure 4). Without KR, intrinsic response-produced feedback must be compared with some internal representation of the goal movement and a difference (error) generated. This intrinsic comparison, previously termed *subjective reinforcement* (Schmidt, 1975), is substituted for the KR. Although the nature of this intrinsic evaluation is undoubtedly less accurate than the KR for updating input–output rules (e.g., recall schema), it may be more beneficial than the KR by preventing maladaptive corrections encouraged when feedback is always available. The subsequent performance drift away from the target behavior represents a kind of bias or CE increase. However, with a larger CE, this drift is readily apparent (when KR is eventually provided), and the nature of the needed correction is perhaps more obvious. In effect, a practice regime with intermittent feedback presentations seems optimal for the facilitation of processes leading to the development of both response consistency and accuracy—two factors considered critical for learning.

Some Similarity With Partial-Reinforcement Effects

The KR relative frequency results presented here show some similarity to the instrumental conditioning work with animals using partial-reinforcement schedules. Indeed, several of the early KR frequency studies were motivated by the belief that there existed general laws of learning that could be applied equally to animals and humans (Seligman, 1970). One widely accepted generalization about the effects of frequency schedules in simple animal conditioning experiments was that resistance to extinction of a conditioned response was greater the lower the relative frequency of reinforcement during initial training (see Mackintosh, 1974, chap. 8, Pt. III, for a review). This observation, known as the *partial-reinforcement effect* (PRE), formed the basis for several corresponding KR frequency studies with humans (e.g., Annett, 1959; Black & Black, 1970; Goldstein & Rittenhouse, 1954; McGuigan, 1959). In most cases, no PRE effects were observed in these human learning experiments, but there were a few exceptions (Baird & Hughes, 1972; Taylor & Noble, 1962), which suggest that, at least superficially, the principles of KR for humans might be similar to those of reinforcement for animals.

The results of Experiment 2 strongly mirror the faded reinforcement research in which decreases in reinforcement across training generally enhanced extinction performance (Lewis, 1960). However, the results of Experiment 3 seem inconsistent with the reinforcement research. In contrast to the work reported here, in instrumental conditioning, one guiding principle for effective reinforcement schedules is the similarity between training and extinction conditions (Mackintosh, 1974). The present findings which argue against a similarity hypothesis are clearly inconsistent with this view and suggest that the mechanisms for human learning with KR may not be the same as those for animal conditioning with reinforcement.

Related Practice Paradigms

The KR relative frequency paradigm is one of several variations that pertain to the scheduling of KR presentations for motor skill acquisition, such as summary KR (e.g., Lavery, 1962; Schmidt et al., 1989), and bandwidth KR (e.g., Lee & Carnahan, in press; Sherwood, 1988). In each of these scheduling paradigms, the learner is compelled into certain information-processing strategies that are associated with a stronger capability for responding than that achieved when KR is provided after every trial. Similar results have been reported for so-called discovery or trial-and-error learning as compared with guided or errorless learning, as well as certain generative learning techniques in education (e.g., Prather, 1971; Singer & Pease, 1976; Wittrock, 1974).

The beneficial effect of these KR variations suggests that factors other than the number of KP presentations are critical for learning. Emphasis is placed not only on how KR is used when it is provided but also on the contribution of the practice trials for which KR is not provided and the associated processes thereby invoked. On the basis of the KR guidance view, and several alternative perspectives pertaining to spaced-retrieval practice and response variability, several plausible mechanisms have been explored. However, a more complete understanding of those factors responsible for the beneficial effects from these KR variations will be important for new developments in both theory and practice.

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