DO THE PRINCIPLES OF MOTOR PROGRAM EDITING APPLY TO LONGER SEQUENCES OF RAPID AIMING MOVEMENTS? PART II

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ABSTRACT

Int J Exerc Sci 1(2) : 50-61, 2008. In Part I of this study, it was shown that performing a shorter distance aiming movement prior to a longer distance aiming movement resulted in overshooting of the short movement and undershooting of the longer movement compared to control conditions. However, the finding was limited, unexpectedly, to the nondominant hand. To replicate the prior result and to determine the effect of practice organization on movement accuracy, right-handed (n =24) participants (aged 18-22) produced a sequence of three rapid lever reversals combining short (20°) and long (60°) movements with an intermovement interval of 2.5 s with the dominant hand. Greater overshooting of the short movements and greater undershooting of the long movement was shown with random practice compared to blocked practice for both same distance and different distance sequences, although spatial errors were greater in the different conditions compared to the same conditions. Overall, the experiment demonstrated parameter value switching and practice organization as two major sources of spatial inaccuracy in sequential aiming movements.

KEY WORDS: Aiming accuracy, task switching, movement consistency, practice organization

INTRODUCTION

Determining the factors that influence the accuracy of rapid aiming movements has been the focus of research for over 100 years. Early line drawing investigations by Hollingworth (3) and Woodworth (23) sought to establish the relation between kinematic variables such as amplitude, movement time, velocity, and spatial accuracy. These early studies demonstrated that movement accuracy diminished as movement speed increased. This work on speed and accuracy culminated in the establishment of Fitts' Law (2), which confirmed many of Woodworth's (23) findings. Fitts' work was later extended by Schmidt et al. (13) who demonstrated that spatial error in rapid aiming tasks was directly related to amplitude and inversely related to movement time. Moreover, spatial error was found to be positively related to the ratio of amplitude/movement time (average velocity).

Although aiming accuracy is clearly related to movement speed and distance, research has shown that accuracy is also affected by the context in which the movement is performed. For example, if two aiming movements covering different distances are performed simultaneously, the shorter distance movement will overshoot its target and the longer distance movement will undershoot its target (21) relative to when same distance movements are performed. Similar effects on accuracy have been shown when sequences of aiming movements are performed. In such cases where one alternates shorter and longer distance aiming movements, biasing effects occur whereby the shorter distance movements overshoot and the longer distance movements undershoot relative to non-alternating control conditions (18, 22). These biasing effects are called assimilations since the shorter distance movement approximates the longer distance movement and vice versa for the longer distance movement (18).

According to Rosenbaum et al.'s (9) program-editing hypothesis, assimilation effects in movement sequences are due to interference in the parameter specification process during the construction of the generalized motor program (GMP). Based on GMP theory, different sequential aiming movements are accomplished by changing an amplitude scaling parameter while maintaining invariant features like relative timing and sequencing (4, 12, 14). According to this view, the GMP is retrieved from long-term memory while the appropriate amplitude parameter is selected from a recall schema or a similar memory structure. The program is integrated with the parameter in working memory and the program is constructed and initiated during response production (12). According to Rosenbaum et al. (9), interference effects in sequential movements are caused by changing the value of a motor program parameter on consecutive movements. Accordingly, they suggested that the response programming processes were made more efficient by changing only the value of the parameter as needed, while maintaining the basic motor program. Support for this program-editing hypothesis has been provided by Rosenbaum et al. (9) in a variety of sequential keyboarding tasks by showing that speed and accuracy of sequential movements were enhanced when the same movement was repeated. However, interference occurred when a parameter value was changed between movements resulting in slower and more inaccurate responses. If the same concepts of program editing generalize to the current sequential aiming movements, then performing two same-distance movements consecutively would not result in any interference. However, performing a long movement before a short movement should result in overshooting of the short movement relative to same distance conditions. Performing a short movement before a long movement would result in undershooting of the long movement relative to long-long movement conditions.

However, recent tests of Rosenbaum et al.'s (9) model involving sequences of rapid aiming movements have produced mixed results. For example, in two-sequence aiming movements, Sherwood (18) showed assimilation effects in both short and long aiming movements when they were combined with different length movements. However, the main limitation of the work by Sherwood (18) was that only two movements were made in a given sequence, substantially shorter than the sequences used by Rosenbaum et al. (9). Work by

Wilson and Sherwood (22) in Part I of this study extended the efforts of Sherwood (18) by asking participants to make three rapid aiming movements in sequence (called "triplets"). The triplets either repeated the same distance or alternated short (20°) or long (60°) movements. When the long movement occurred in the middle of the triplet and was preceded and followed by short movements, undershooting was 5% greater than the control condition. When the short movement occurred at the end of the triplet, preceded by the short and long movement, greater overshooting was shown compared to the control condition. Surprisingly, assimilation effects were only found for the nondominant hand, not the dominant hand, as in prior work (18). Even though the results from Part I of the study (22) are not consistent with earlier work (18), they do suggest that the principles of program editing only apply to conditions involving the nondominant hand. The lack of interference effects on the dominant hand in Part I of the study (22) provided the main rationale for the current experiment where the dominant hand was used exclusively.

Another surprising finding from Part I of the study (22) was that overshooting was shown on the short movement beginning each triplet, particularly if the second movement in the sequence was the long movement. Such overshooting was probably due to interference generated by the random practice order used in the experiment. In order to prevent participants from anticipating the sequence on a given trial, the three sequences (short-short-short, short-long-short, or short-no movement-short) were presented in a different random order for each participant. The use of random practice probably encouraged the participants to be prepared to produce any sequence on any given trial. The use of this strategy implies that both the short and long movement parameters would be held in working memory throughout practice, providing the basis for interference. As predicted by the elaborative processing hypothesis (5, 15, 16) interference between program parameters in working memory causes interference in the response production process. Interference is maximized when participants must perform sequences consisting of different distance movements regardless of whether random or blocked practice is used. However, in blocked practice, where the same movement sequence is repeated on each trial, multiple program parameters may not be stored in working memory, reducing or eliminating interference effects. Evidently, this interference in working memory results in an overproduction of the force parameter for the short distance under random practice conditions (19).

As mentioned earlier, one surprising finding of Part I of the study (22) was the lack of an interference effect on the dominant hand. In order to replicate this finding, the current experiment investigated the effects of parameter value switching on the dominant hand only. If no effects of parameter value switching are found for the dominant hand then the principles of program editing will be significantly limited. Finally, the question of whether the overshooting of the first movement of the sequence was due to the random order of the sequential practice trials was examined by contrasting a blocked practice order with a random practice order.

METHOD

Participants
The participants were 24 male and female undergraduate students (aged 18-23) at the University of Colorado who had not volunteered for Part I of this study (22). Inclusion criteria included right-handedness based on the Edinburgh Handedness Inventory (8) and not having previous experience with the task. All participants received course credit equal to 1% of their final course grade for their participation. The Human Research Committee at the University of Colorado approved the work and the participants signed an informed consent form before participating.

Apparatus
The apparatus was the same as in Part I of this study (22). For examples of the potentiometer output and a photograph of the apparatus see Part I of this study (22).

Task
The task and procedures were the same as in Part I of this study (22) except for the following details. The short (20°) and long (60°) reversal movements were made using only the dominant hand. Four different triplets were performed, short-short-short (SSS), short-short-long (SSL), long-long-long (LLL), and long-long-short (LLS) in either a blocked or a random order based on randomized group assignment. Participants in the blocked practice group (n = 16) were randomly assigned to one of two practice orders. The order for the short-long blocked practice group (B-SL, n=8) was SSS, LLL, SSL and LLS. The order for the long-short blocked practice group (B-LS, n=8) was LLL, SSS, LLS, and SSL. Prior to testing, participants in the blocked practice groups were told that the same sequence would be repeated on each trial of a given set of trials. Random practice participants were told that any of the four sequences could be requested on any practice trial. To determine the trial order for each participant (n =8) in the random practice group (R) a deck of 60 index cards was made. On each card was listed one of the four possible sequences, 15 from each condition. The deck was shuffled at least 5 times prior to testing resulting in a unique trial order for each participant. Participants performed 60 trials, 15 for each sequence.

Data analysis
Spatial accuracy and consistency for both groups was determined from the potentiometer output by computing the constant error (CE) and variable error (VE), respectively, in the reversal point for each movement for each participant using the last 14 trials from each of the four sequential movement conditions. Analyses involving CE, VE, and MT used mixed factorial designs with repeated measures. The analysis of the last movement of the triplet was accomplished with 3 (Group: Random/Blocked SL/Blocked LS) x 2 (Condition: Same/Different) x 2 (Distance: Long/Short) ANOVAs with repeated measures on the last two factors. To determine whether any change in accuracy or trial to trial variability occurs with repetition of the same movement, the CE and the VE of the reversal points from the SSS and LLL sequences were analyzed with a 3 (Group: Random/Blocked SL/Blocked LS) x 2 (Distance: Short/Long) x 3 (Movement: First, Second, Third) ANOVA with repeated measures on the last two factors. The same distance movements from

the SSL and LLS sequences were analyzed with a 3 (Group: Random/Blocked SL/Blocked LS) x 2 (Distance: Short/Long) x 2 (Movement: First/Second) ANOVA with repeated measures on the last two factors.

Mean relative times were computed as in Part I of this study (22) for each reversal point for each participant for the last 14 trials per sequence. Comparing the relative times of the reversal points was done with a 2 (Group: Dominant/Nondominant) x 4 (Condition: SSS, LLL, SSL, LLS) x 3 (Movement: First/Second/Third) with repeated measures on the last two factors.

RESULTS

Relative Timing

The relative timing of the three reversal points was 6%, 13%, and 93%, respectively, averaged over all groups and conditions. There was a significant effect of movement, $F_{(2,54)} = 1845.4$, $p < .001$, $\eta^2=.99$. No other effects were significant.

Comparing the Last Movement In the Sequence

Figure 1 shows the mean CE for the last movement in the triplet for all four sequences plotted by group where the two blocked groups have been combined. In general, the short movement showed positive CEs and the long distance negative CEs as expected. However, the magnitude of the errors apparently depended on distance, practice organization and whether a parameter value change was required. The short movement was overshot, particularly when preceded by two long movements and in the random practice condition, compared to the SSS control sequence and the blocked practice condition. The long movements were undershot, but only slightly more undershooting was shown for the random group in the SSL condition compared to the LLL condition.

However, only the two-way interaction between distance and condition was significant, $F_{(1,27)} = 18.3$, $p < .001$, $\eta^2=.41$, not the three-way interaction between distance, group and condition. Main effects of distance, $F_{(1,27)} = 54.8$, $p < .001$, $\eta^2=.67$, condition, $F_{(1,27)} = 4.5$, $p < .05$, $\eta^2=.14$, and group, $F_{(2,27)} = 4.2$, $p < .05$, $\eta^2=.24$, were significant. LSD post-hoc tests revealed that the random practice group had significantly greater errors than both of the blocked practice groups. The blocked practice groups were not significantly different.

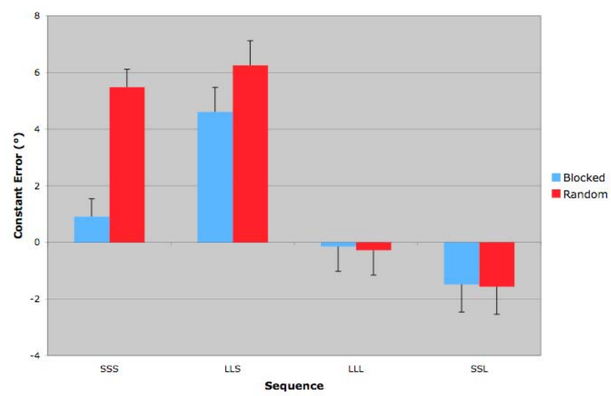

Figure 1. The mean constant error for the last movement of the short-short-short (SSS), long-long-short (LLS), long-long-long (LLL) and short-short-long (SSL) sequences for both blocked and random practice groups. Standard errors are also indicated.

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of distance, $F_{(1,27)}$ = 54.8, p < .001, η^2=.67, condition, $F_{(1,27)}$ = 4.5, p < .05, η^2=.14, and group, $F_{(2,27)}$ = 4.2, p < .05, η^2=.24, were significant. LSD post-hoc tests revealed that the random practice group had significantly greater errors than both of the blocked practice groups. The blocked practice groups were not significantly different.

Participants were more variable producing the requested sequences in the random practice condition compared to the blocked practice condition, particularly when two short movements preceded the long movement, and in the SSS sequence (figure 2). The interaction between group, distance and condition was significant, $F_{(2,27)}$ = 6.9, p < .01, η^2=.34. Main effects of distance, $F_{(1,27)}$ = 13.4, p < .001, η^2=.33, condition, $F_{(1,27)}$ = 4.6, p < .05, η^2=.15, and group, $F_{(2,27)}$ = 4.6, p < .05, η^2=.26, were significant. The mean MTs were 215 and 269 ms, respectively, for the short and long movements. The effect of distance was significant, $F_{(1,27)}$ = 118.5, p < .001, η^2=.81.

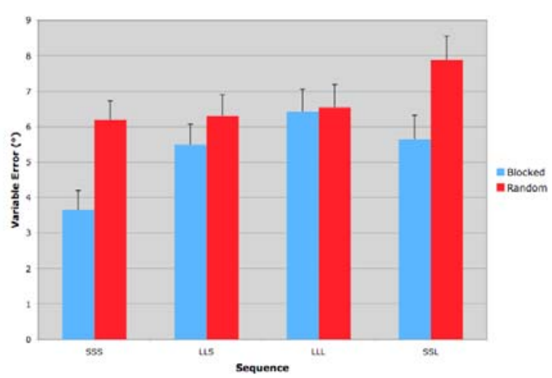

Figure 2. The mean variable error for the last movement of the short-short-short (SSS), long-long-short (LLS), long-long-long (LLL) and short-short-long (SSL) sequences for both blocked and random practice groups. Standard errors are also indicated.

Effects of Maintaining the Same Program Parameter

The design of the experiment allowed for two tests of the prediction that movements would be more accurate and consistent if the same movement distance was repeated during the triplet, either throughout the SSS and LLL sequences or between the first and second movements of the SSL and LLS sequences. Figure 3 shows the mean CE when the short and long movements were repeated three times in either the SSS or the LLL sequences for both the random and blocked groups.

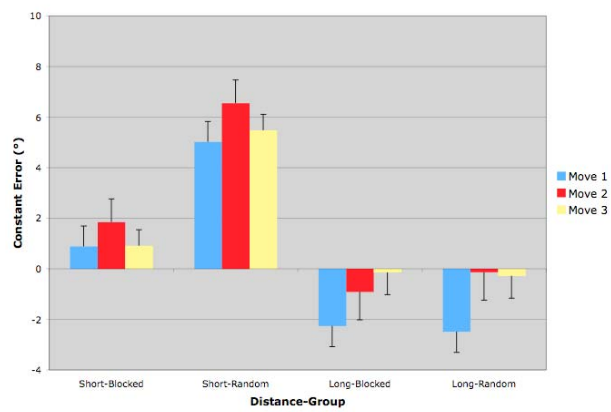

Figure 3. The mean constant error for the three movements of the short-short-short (Short) and the long-long-long (Long) sequences for both blocked and random practice groups. Standard errors are also indicated.

In general, there was little improvement in accuracy between the first and last movements of the triplet. Slightly less undershooting was shown for the long distance movements as the sequence progressed, but accuracy suffered between the first and second movements of the short distance sequences. The same general pattern of results was shown for both the blocked and the random groups. The

Distance x Movement interaction was significant, $F_{(2,54)} = 7.5$, $p < .01$, $\eta^2=.22$. Main effects of distance, $F_{(1,27)} = 38.4$, $p < .001$, $\eta^2=.59$, and movement, $F_{(2,54)} = 9.6$, $p < .001$, $\eta^2=.26$, were significant. Variable error for the three movements of the SSS sequence were 4.6°, 4.4°, and 4.5°, respectively. The corresponding VEs for the LLL sequence were 6.3°, 5.6°, and 6.5°. The reduction in VE from the first to the second movement for both the SSS and LLL sequences resulted in a significant effect for movement, $F_{(2,54)} = 4.5$, $p < .05$, $\eta^2=.14$. The effect of distance was also significant, $F_{(1,27)} = 45.0$, $p <.001$, $\eta^2=.62$. There was no significant change in MT over either the SSS or the LLL sequence.

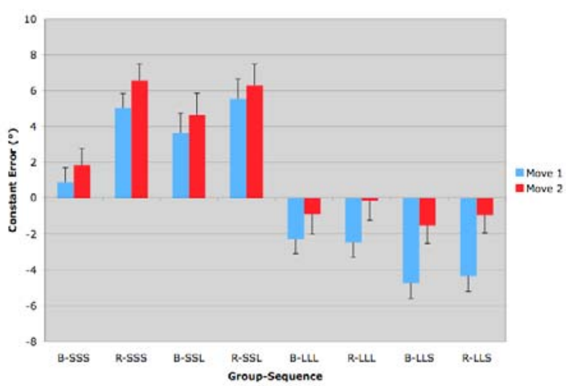

Figure 4. The mean constant error for the first two movements of the short-short-short (SSS), long-long-short (LLS), long-long-long (LLL) and short-short-long (SSL) sequences for both blocked (B) and random (R) practice groups. Standard errors are also indicated.

Figure 4 shows the constant error for the first two movements for all sequences for both blocked and random practice groups. Accuracy suffered between the first two short movements but improved for the long movements. The improvement in the long movement appeared to be greater for the LLS sequence while the decrement in accuracy for the short movement was the highest for the SSS sequence. This pattern of findings here resulted in a three-way interaction between condition, movement and group, $F_{(2,27)} = 3.4$, $p < .05$, $\eta^2= .20$. The Distance x Condition interaction was also significant, $F_{(1,27)} = 20.2$, $p < .001$, $\eta^2= .43$.

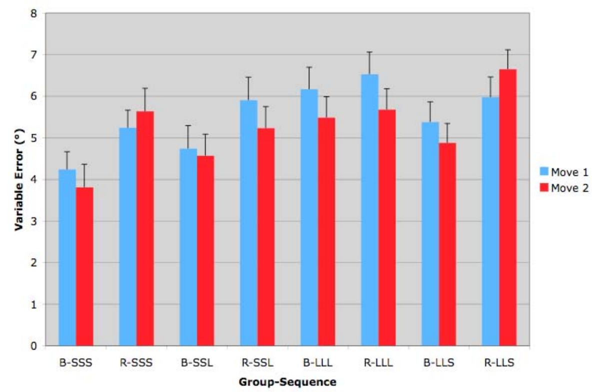

Figure 5. The mean variable error for the first two movements of the short-short-short (SSS), long-long-short (LLS), long-long-long (LLL) and short-short-long (SSL) sequences for both blocked (B) and random (R) practice groups. Standard errors are also indicated.

The mean VEs for the first two movements for all sequences are shown in Figure 5. In general, participants were more consistent on the second movement of the sequence, except for the random group in the SSS and LLS sequences. The reduction in variability appeared to be the greatest in the SSL and LLL sequences for the random group and in the LLL for the blocked group. The differences between groups and conditions described here resulted in a four-way interaction between group, condition, distance and movement, $F_{(2,27)} = 3.6$, $p < .05$, $\eta^2 = .21$. The interaction between distance, condition, and group was also significant, $F_{(2,27)} = 6.3$, $p < 01$, $\eta^2 = .32$. Main effects for movement, $F_{(1,27)} = 10.9$, $p < .01$, $\eta^2 = .29$, distance, $F_{(1,27)} = 15.7$, $p < .001$, $\eta^2=.37$, and group, $F_{(2,27)} = 4.6$, $p < .05$, $\eta^2=.25$, were all significant.

Movement time increased slightly for the short distance between the first (M = 215 ms) and second (M = 218 ms) movements, but decreased for the long distance between the two movements (M = 268 ms to M = 264 ms). The Distance x Movement interaction was significant, $F_{(1,27)} = 4.9$, $p < .05$, $\eta^2=.16$. The effect of distance was also significant, $F_{(1,27)} = 103.2$, $P < .001$, $\eta^2=.79$.

DISCUSSION

The main goals of the experiment were to determine if the principles of motor program editing generalize to rapid aiming movements of the dominant hand and to determine how blocked and random practice influence movement accuracy and consistency.

Evaluation of the Program Editing Hypothesis

As predicted by the program-editing hypothesis (9), short movements preceded by two long movements overshot compared to same distance control conditions. Long movements preceded by two short movements undershot compared to the control conditions. Interestingly, the magnitude of the interference effects was greater in the current experiment compared to the earlier work (22). In Part I of the study we showed when one long movement preceded a final short movement, slight and nonsignificant undershooting of the last movement occurred in the dominant hand with no increase in VE over control conditions (22). When two long movements preceded the final short movement in the current experiment, overshooting of 4-6° was shown with an increase in VE from 4.5° to 5.8° compared to the SSS sequence. The findings here suggest that the interference due to program parameter editing can affect the dominant hand, as long as prior movements have generated a sufficient amount of interference. It could have been that a sequence of only two different movements did not generate enough interference to influence the dominant hand in the prior work (18). These results support Rosenbaum et al's (9) program-editing approach to motor programming described earlier. When a change in the parameter value is called for in the SSL and LLS sequences, interference occurs resulting in overshooting or undershooting.

However, the second prediction of the program-editing hypothesis, that movements would be more accurate and consistent when repeated was only partially supported. In Part I of the study (22), repetition of the short movement in the SSS sequence resulted in greater overshooting of the second movement compared to the others in the sequence. In the current experiment, long movement accuracy improved as the sequence progressed for the LLL and LLS sequences. However, short movement accuracy suffered as the SSS and SSL progressed. Reductions in VE occurred between the first and second movements of the SSS and LLL sequences, but continued reductions did not extend to the final movement in the sequence. Similar reductions in VE were also noted in the SSL and LLS sequences, but in some cases the results were restricted to either the blocked or random practice groups. Overall, the expectation that consistency would improve with repetitions of the same movement was not strongly supported.

It could be that program editing has an effect on CE but not VE. But clearly, many factors can contribute to trial-to-trial variability in addition to the effectiveness of the parameter specification for a particular movement. Participants may evaluate sensory feedback from a particular movement and might choose to modulate the parameter on the next movement in the sequence based on perceived error (12). Also some variation over trials could be due to noise in the neuromuscular system where the movement goal is not translated to the proper level of muscle activation (13, 14). Perhaps with tighter experimental control and more extensive instructions for the participant, the effect of some of these confounding factors could be determined. With regard to the current study it appears that the program-editing hypothesis is best evaluated via CE rather than VE.

Effects of Blocked and Random Practice
In Part I of the study, the overshooting of the short distance on the first sequential movement was thought to be due to interference generated by the random practice order of the movement sequences (22). The assumption supported by this result was that the program parameters for both the short and long movements were concurrently held in working memory. Random practice should generate greater interference compared to blocked practice since the participant should be prepared to perform any of the four sequences on any given trial. Random practice resulted in large spatial errors for all movements of the sequence, particularly for the short distance. Overshooting of 5°- 6° was shown for the short distance and 1°- 2° of undershooting for the long distance. On the other hand, blocked practice resulted in much smaller spatial errors (typically < 2°), particularly when no parameter value change was required. In other words, random practice resulted in greater overshooting compared to blocked practice even when the goal was to produce the same distance on all movements in the sequence. The only condition in which blocked practice resulted in relatively large errors was in the LLS condition where the interference from the long movements caused overshooting of the short movement. Random practice also caused greater trial-to-trial variability compared to blocked practice. These findings strongly support interference in working memory as the basis for the accuracy and variability findings. According to the elaboration hypothesis (5, 15, 16), both the short and long movement parameters are stored in working memory during random practice allowing for biasing to take place. This biasing results in an overproduction of the force parameter controlling the short distance movement regardless of where the movement is made in the sequence. This finding confirms a large body of work showing the disadvantages of random practice relative to blocked practice for motor performance (5), but the current work extends this body of work by describing the directional bias created by practice schedule variations. However, the current results do not in any way negate or conflict with the numerous studies showing the advantages of random

practice compared to blocked practice on retention and transfer tests (1, 5, 15, 16, 24).

These findings imply that teachers, coaches, physical therapists, and other professionals who use random practice schedules should not be surprised when performance suffers compared to blocked practice conditions. Perhaps learners could be made aware of the biasing effects that may exist when programs and/or parameters are varied from trial to trial. However, the point should be made that such decrements in performance are only temporary, and learning will be more effective in the long term following the challenges of random practice.

Implications for Other Theories of Motor Learning and Control

The current results along with those from Part I of the study (22), have shown that alternating short and long aiming movements causes greater errors compared to the repetition of the same movement. The alternating movement condition in the current experiment is analogous to a variable practice condition where program parameters are varied while maintaining the relative timing of the motor program. However, despite the increased errors noted during practice, it is unlikely that such errors would weaken the recall schema or retard transfer to novel movements. Research has shown that variable practice conditions that produce elevated errors during acquisition, result in better retention and transfer to novel movements (17). These findings support the prediction from schema theory that all movements strengthen the schemata as long as one is aware of the parameter used on a given trial, the sensory feedback generated by the movement, and the movement outcome (10, 11, 12, 20).

The current results also confirm our earlier work (22) showing that movement accuracy in sequential aiming movements is a function of both kinematic factors and contextual interference. In single aiming movements spatial movement accuracy and consistency decrease as movement distance increases and as movement time decreases (13, 14), a finding supported by some of the main effects in the current study. For example, short movements were more consistent than long movements regardless of whether they were preceded by short or long movements (Figure 2). Also, short movements were more consistent than long movements when the same movements were repeated early in the sequence (Figure 5). But when sequences of aiming movements are made, accuracy and consistency is a function of two sources of contextual interference. Contextual interference is produced by requiring a change in the program parameters within a sequence, which results in assimilation effects compared to repeated movement conditions. Secondly, higher levels of contextual interference are generated by random practice compared to blocked practice. It is clear that models of movement control based on discrete aiming movements (6, 7, 13, 14) cannot account for the principles of movement accuracy that emerge when sequential aiming movements are performed.

In summary, it is clear that the program-editing hypothesis can account for interference between rapid aiming movements when a change in the value of the program parameter must be made, but the prediction that accuracy and variability improves when the same movement is repeated was not strongly supported. Our current and recent (22) experiments have shown that producing accurate aiming movements involves more than simply selecting appropriate force parameters from working memory and constructing the GMP accordingly. Accuracy is influenced both by the need to change the value of the program parameter and the structure of practice.

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