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

ERIC J. WILSON* and DAVID E. SHERWOOD‡

Department of Integrative Physiology, University of Colorado, Boulder, CO, USA

*Denotes undergraduate student author, ‡denotes professional author

ABSTRACT

Int J Exerc Sci 1(1) : 30-42, 2008. Prior work had 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 repetition of the same movement. The main question was whether the same interference effects would be found in a three-movement sequence. Right-handed (N = 24) participants (aged 18-22) produced a sequence of two or three bimanual rapid lever reversals combining short (20°) and long (60°) movements with an intermovement interval of 2.5 s beginning with either the dominant or nondominant hand. Participants overshot the short target and undershot the long target when short and long movements alternated compared to same distance control conditions, but the effects were greater for the nondominant hand. Overall, the experiment demonstrated that parameter value switching was a major source of spatial inaccuracy in sequential aiming movements.

KEY WORDS: Aiming accuracy, task switching, movement consistency, generalized motor programs

INTRODUCTION

According to motor control theory, centrally stored motor programs control rapid limb movements. Motor programs control movement in an open-loop fashion by activating the appropriate muscles with a consistent timing pattern without the need of sensory feedback present in closed-loop control (10). Motor programs are also thought to be somewhat flexible so the same program can be used to achieve different movement goals. According to this notion of a generalized motor program (GMP), rapid aiming movements are controlled by selecting the program from long-term memory and then applying force and/or duration parameters to meet the specific spatial and temporal goals of the task (3-4, 10). Each GMP is defined by so-called invariant features (order of events, relative timing, relative force) that remain constant over practice trials and distinguish the program from other GMPs. However, the force and time parameters can be varied independently or in conjunction with one another to allow a single GMP to achieve a variety of movement outcomes. For example, increasing the force parameter and maintaining the time parameter results in longer distance movements but maintains movement time. Increasing the force parameter and decreasing the time parameter accomplishes faster movements with shorter durations. The process of "constructing" the motor program by applying appropriate force and/or time parameters is assumed to take place in working memory. Predictions from this approach to motor programming have been upheld in several studies involving single aiming movements demonstrating that peak force is directly related to movement distance and inversely related to movement time, while the force duration is directly related to movement time (12-15, 21).

Understandably, much of the earlier work on the programming of aiming movements involved single discrete movements due to the ease of modeling the GMP and the associated force and time parameters. Recently, researchers have begun to investigate the motor programming process in sequential actions requiring the completion of a series of movements. For example, Rosenbaum et al., proposed that when the same movement is performed repeatedly the motor programming processes were made more efficient by editing only the value of the force or time parameter as needed, while maintaining the GMP (6). However, if one is required to change the value of the force or time parameter from movement to movement, then interference occurs in the programming process. In a variety of memorized sequential keyboarding tasks, Rosenbaum et al. showed speed and accuracy of sequential movements were enhanced in same movement conditions, presumably due to the preservation of the value of a given parameter from movement to movement (6). However, interference occurred when a parameter value was changed between movements resulting in slower and more inaccurate responses. Rosenbaum et al. also reported that errors generally decreased as the length of the sequence increased from three to nine movements (6). More recent research has shown that these concepts of program editing generalize to sequential aiming movements. For example, Sherwood, using the same task as the present experiment, has shown that performing a longer distance aiming movement before a shorter distance aiming movement results in overshooting of the short movement relative to same distance control conditions (22). Also, performing a shorter distance aiming movement before a longer distance movement resulted in undershooting of the longer movement relative to longer movement control conditions. The same interference effects were shown when both hands or a single hand performed the movement sequence. The interference effects noted here could have been the result of holding both the short and long program parameters in working memory at the same time making selection of the proper parameter value more difficult. However, the main limitation of the work by Sherwood was that only two movements were made in a given sequence (22). In order to make valid comparisons with the earlier work on keyboarding tasks, aiming movement sequences of at least 3 movements are required.

Therefore, the main question for the present experiment was whether the principles of program editing would apply to longer sequences of aiming movements (i.e., three movements). If the principles of program editing also apply to longer movement sequences than one would expect movements to be more consistent and accurate when the same movement is repeated compared to a sequence where the force and/or time parameter value is changed during the sequence. The main advantage of using aiming movements instead of keyboarding tasks to extend the principles of program editing is that the specific biasing effect (either overshooting or undershooting) of the interference can be identified. Assuming that the program parameters are held in working memory at the same time (2), changing the force parameter value should cause a biasing effect on the following movement. If interference in aiming movements follows the principles of program editing, the findings should have implications for manual control tasks (e.g., hammering a nail) and sport tasks (e.g., tennis) where force must be modulated from movement to movement.

METHOD

Participants

The participants were 24 undergraduate students (aged 18-22, male N = 10, female N = 14) at the University of Colorado. Inclusion criteria included right-handedness based on the Edinburgh Handedness Inventory (5) 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 (shown in Figure 1) was a Plexiglas platform on a standard table top, which was slotted to allow two aluminum hand levers (16 cm in length and 36.5 cm apart) to rotate 75° in the sagittal plane, with the most proximal position called 0°. Precision potentiometers (Beckman Industrial, #3381, 10K) were affixed to the base of each lever so displacement could be recorded. The measurement error of the potentiometers was 0.1°. Due to the arrangement of the hand levers and the potentiometers, the hand and levers moved in a slightly curvilinear path such that the maximum vertical change in displacement of the tip of the lever was 3 cm. The maximum curvilinear distance the levers could travel in the sagittal plane was approximately 22.5 cm. The output of the potentiometers were digitized on-line at 1000 Hz and stored on a PC. An interval timer (Lafayette Instruments, Model 52011) was used to control the intermovement interval.

Figure 1. The lever apparatus used in the experiment.

Task

In order to provide a valid extension of the previous work (22) to a three-movement sequence the same task was used with the addition of a third movement. Accordingly, the task for the subject was to make rapid reversal movements one hand at a time, first singly, then in a two- or three-movement sequence. The interval timer was used to maintain 2.5 s between the initiation of the first and last movements of the sequence. The participants were instructed to make smooth movements out to the reversal point and back to the 0° starting position, without waiting or hesitating at the reversal point. When the movements were performed correctly, the output of the potentiometers were bell-shaped, but with a distinct peak at the reversal point (see Figure 3). The movement to the reversal point required extension at the elbow joint and flexion at the shoulder joint. Returning the lever to the start position involved flexion at the elbow joint and extension of the shoulder joint. It should be emphasized that there were no target zones; instead, the participant attempted to reverse the lever at the 20° (short) or the 60° (long) point along the path of the lever. Combinations of short and long reversal movements were used to create three movement sequences, either three short movements in succession (short-short-short, or SSS), or alternating short and long movements, (short-long-short, or SLS), or performing two short movements separated in time (short-no movement-short, SNS). The sequences were initiated with either the dominant or non-dominant hand and completed by alternating hands. As such, the same hand completed the first and third movements in the SSS and SLS sequence with the second movement made by the opposite hand. The same hand completed both movements in the SNS sequence. The goal time to reversal (hereafter called movement time, MT) was 210 ms for each movement regardless of movement distance. The starting point for all movements was the 0° position. Even though the movement time goal was likely short enough to prevent the use of visually based movement corrections (10), participants were prevented from viewing their hands by placing a frame-supported opaque sheet over the apparatus and the participant's arms. By preventing the use of visual feedback in this manner, it was assumed that the participants would be encouraged to program all of the movements rather than relying on some form of closed-loop control. See Figure 2 for a photograph of a participant in the testing position.

Figure 2. A participant in the testing position. The apparatus is covered by a wooden frame and sheet.

Figure 3 shows the position-time record for one trial for one participant from the SLS sequence. Points A and B, C and D, and E and F in the figure show the onset and reversal point for each movement, respectively. The duration between A and B, C and D, and E and F indicate the MT for each movement. In addition, one can describe the relative timing of movement pattern by characterizing when each peak occurs relative to the total time from the onset of the first movement (Figure 3, point

A) to the offset of the last movement (Figure 3, point G). For the sample data in Figure 3, the relative time of the three reversal points was 6%, 40% and 94%, for the first, second, and third points, respectively.

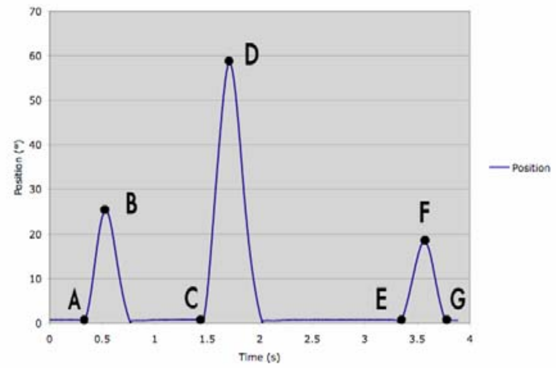

Figure 3. A sample position-time record from one participant from one trial from the SLS sequence. Onset and reversal points are indicated for each movement including the offset point for the last movement in the sequence.

Procedures

Participants were randomly assigned to one of two groups (N = 12). Table 1 shows the practice order for the single practice trials for both groups. As indicated in the table, the dominant group began single practice and all sequences using the dominant (right) hand and the nondominant group the left hand, respectively. Practice began with single practice trials where the short and long movements were practiced one at a time in blocks of 15 trials. As shown in Table 1, one-half of the participants practiced the short movement before the long movement while the other half practiced with the opposite order. Following the single practice trials, each participant performed 30 sequential practice trials, 10 each of the SSS, SLS, and SNS versions in a random order. To determine the trial order for each participant a "deck" of 30 index cards was made. On each card was listed one of the three possible sequences, 10 from each condition. The deck was shuffled at least 5 times prior to testing resulting in a unique trial order for each participant. The deck was not re-ordered between participants.

Each trial began with the participant sitting in a standard chair in front of the apparatus and grasping the upper portion of the appropriate lever(s) so that the upper arm was vertical and the elbow joint was 90°. On the single practice trials, when a brief single auditory stimulus was given, the participant attempted to move the lever to the goal reversal point and back to the starting position. Five seconds after completing the movement, the experimenter gave knowledge of results (KR) about the accuracy of the reversal point to the nearest degree. At the beginning of each sequential trial, the experimenter directed the participant to attempt one of the three sequential movement patterns (SSS, SLS, or SNS). Two auditory stimuli were given 3.1 seconds apart (controlled by the interval timer) to initiate the sequential movements[1]. Participants were instructed to make the first two movements of the three-movement sequence beginning with the first auditory stimulus, and make the final movement in response to the second stimulus. In the SNS condition the two short movements were made in response to the first and second auditory stimuli, respectively. After the sequence was completed spatial KR was given about all movements. Precise feedback was given about the reversal point in both single and sequential conditions to

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[1] Pilot testing had shown that an interstimulus interval of 3.1 s resulted in an intermovement interval of about 2.5 s. The longer interstimulus interval allowed for reaction time to the first stimulus and the completion of the first two reversal movements.

Table 1. Practice Order for the Four Blocks of Single Practice Trials for the Dominant and Nondominant Groups

Group	Single 1	Single 2	Single 3	Single 4
Dominant (n=6)	RH-Short	RH-Long	LH-Short	LH-Long
Dominant (n=6)	RH-Long	RH-Short	LH-Long	LH-Short
Nondominant (n=6)	LH-Short	LH-Long	RH-Short	RH-Long
Nondominant (n=6)	LH-Long	LH-Short	RH-Long	RH-Short

Note: LH is left hand and RH is right hand.

focus the participant's attention on that characteristic so they could make any needed correction on the next practice trial. By using KR on every trial it was assumed that the participants would use this information to effectively guide the hand to the appropriate spatial target (7). Participants were given only qualitative KR about MT ("Too slow" or "Too fast") for all trials if the MT from any movement was greater than 231 ms or less than 189 ms, respectively. Accordingly, less precise KR was provided about MT since temporal error was not a focus of the current study and we wished to avoid overloading the participant with too much augmented feedback. Giving temporal feedback using this bandwidth approach was also intended to enhance temporal consistency by only requiring a correction in MT if the performance was outside of an acceptable range (18). If the participant did not return to the 0° position between movements the participant was informed of this and the trial repeated.

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. In order to standardize the number of trials involved in the calculation of the means, only the last 10 single trials were used to compare with the mean based on each set of 10 sequential trials. Constant error indexes the average amount of overshooting or undershooting relative to the goal distance. For example, if a participant averages 18° over a set of trials with a goal of 20°, the CE would be -2°. Overshoots would result in positive CEs. Variable error is the within-subject standard deviation computed for each participant over a given set of trials. The mean MT was also computed using the same sets of trials as described above for the single and sequential movements.

The relative time of each of the reversal points was determined by dividing the time of each point (i.e., the duration between points A and B, A and D, and A and F in Figure 3) by the total duration of each trial (duration between points A and G, Figure 3). Mean relative times were computed for each reversal point for each participant for each set of 10 sequential trials.

Analyses involving CE, VE, and MT used mixed factorial designs with repeated measures. The CE and VE of the single short movements were compared with the first sequential movement with separate 2 (Group: Dominant/Nondominant) x 4 (Condition: Single, SSS, SLS, SNS) ANOVAs with repeated measures on the second factor. The CE and VE of the long movement in the single and sequential movements were compared with the sequential movements with separate 2 (Group: Dominant/Nondominant) x 2 (Condition: Single, SLS) ANOVAs with repeated measures on the second factor. To assess the effect of changing or maintaining the program parameter on the CE and VE of the first and last movements in the sequence were compared with a 2 (Group: Dominant/Nondominant) x 3 (Condition: SSS, SLS, SNS) x 2 (Movement: First/Last) with repeated measures on the last two factors. The analyses described here were repeated with MT as the dependent variable. Comparing the relative times of the reversal points were done with a 2 (Group: Dominant/Nondominant) x 3 (Condition: SSS, SLS, SNS) x 2 (Movement: First/Last) with repeated measures on the last two factors or a 2 (Group: Dominant/Nondominant) x 2 (Condition: SSS, SLS) x 3 (Movement: First/Second/Third) with repeated measures on the last two factors.

Finally, 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 point from the SSS and SNS conditions were analyzed with either a 2 (Group: Dominant/Nondominant) x 3 (Movement: First, Second, Third) ANOVA with repeated measures on the last factor or a 2 (Group: Dominant/Nondominant) x 2 (Movement: First/Last) ANOVA with repeated measures on the last factor.

RESULTS

Comparing Sequential Movements

The CE for the first and last movements from the sequential conditions is shown in Figure 4 for both dominant and nondominant hands. The amount of overshooting between the first and last movement increased in all conditions except for the dominant hand in the SLS

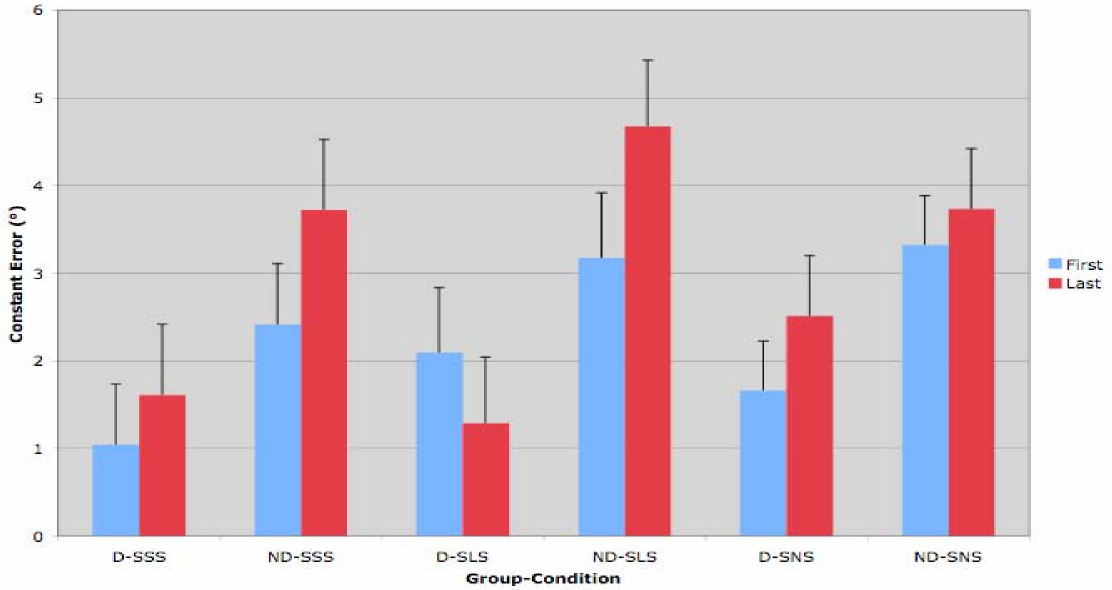

Figure 4. The mean constant error for the first and last movements in the SSS, SLS, and SNS sequences for both the dominant and nondominant hand groups. Standard error bars are also shown.

condition. This finding resulted in a three-way interaction between group, condition and movement, $F_{(2,40)} = 3.49$, $P < .05$, $\eta^2=.15$. The main effects of movement, $F_{(1,20)} = 5.35$, $P < .05$, $\eta^2=.21$, and group, $F_{(1,20)} = 5.2$, $P < .05$, $\eta^2=.21$, were also significant. However, there was no effect of changing the parameter value on the mean trial-to-trial variability in the reversal point. The mean VE for the first movement in the sequence was 4.0° compared to 4.1° for the last movement in the sequence. There was no significant change in MT between the first (M = 187 ms) and the last (M = 185 ms) movements in the sequence. The relative time of first, second, and third reversal points was 5%, 25%, and 95%, respectively. Only the effect of movement was significant when comparing the SSS and SLS conditions, $F_{(2,\ 40)} = 6276.10$, $P < .001$, $\eta^2=.99$, and the SSS and SNS conditions, $F_{(1,\ 20)} = 6389.32$, $P < .001$, $\eta^2=.99$.

The CE in the reversal point for the SSS and SNS sequences are shown in Figure 5. Overshooting was noted for all movements, particularly for the second movement in the SSS sequence. The effect of movement was significant for the SSS sequence, $F_{(2,40)} = 57.1$, $P < .001$, $\eta^2=.74$. LSD post-hoc tests confirmed that all means were different from each other. The difference in CE between the first and last movement for the SNS sequence was not significant. There

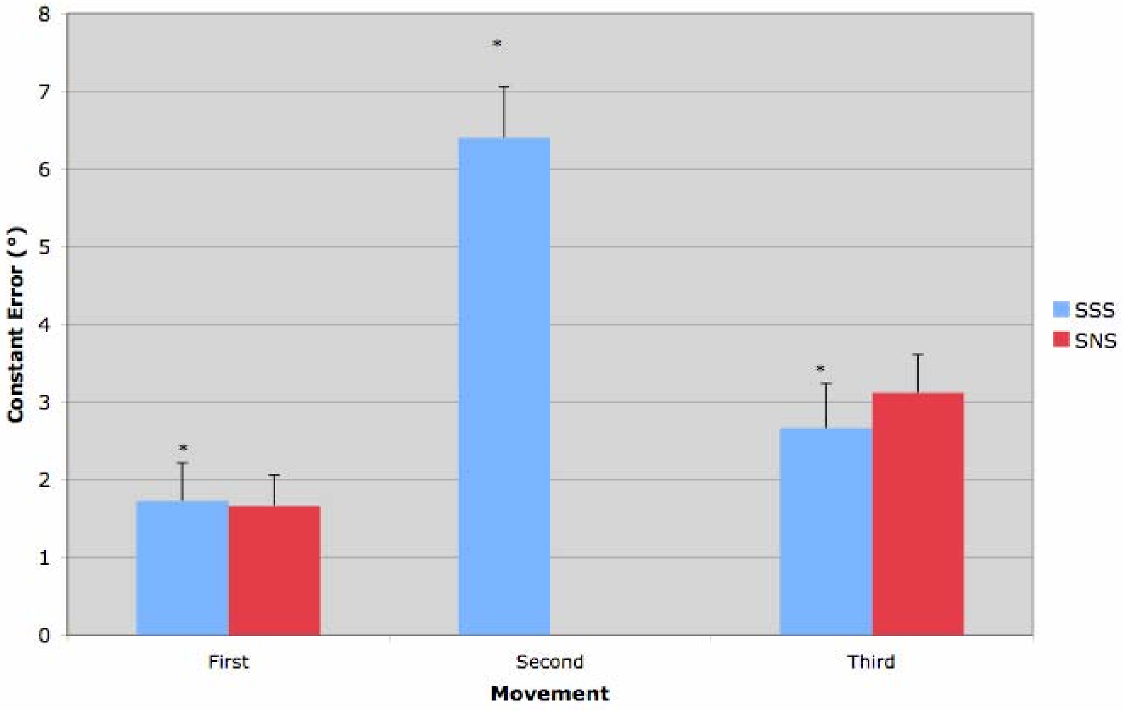

Figure 5. The mean constant error for the movements of the short-short-short (SSS) and short-no movement-short (SNS) sequences. The * indicates that all means are significantly different from each other (p < .05). Standard error bars are also shown.

was no significant change in VE between any of the movements in Figure 5.

Comparing Single and Sequential Movements

Figure 6 shows the mean CE in the reversal point for the single and the first sequential movement for short distance. There was no main effect of group and no significant interaction between group and condition, so the data presented in Figure 6 has been averaged across dominant and nondominant groups. The single movements were very accurate with the average overshooting less than 1°. The short movements initiating the sequences all overshot the 20° goal. The effect of condition was significant, $F_{(3,60)} = 9.0$, $P < .001$, $\eta^2=.31$. LSD post-hoc tests confirmed the mean CE from the single trials was significantly different from the first movement of each sequence. In addition, the CE for the first movement of the SSS sequence was significantly less than the initial movement of the SLS sequence. There was no change in the mean VE for the short distance movement between the single (M = 3.6°) and the sequential conditions (M = 3.9°). The CE for the long movement for the single trials was .4° and was -3.1° for the SLS sequence. The effect of condition was significant, $F_{(1,20)} = 14.8$, $P < .01$, $\eta^2=.43$. The VE in the long reversal point was significantly greater for the SLS condition (M = 6.8°) compared to the single trials (M = 5.3°). The effect of condition was There was no change in the MT of the short

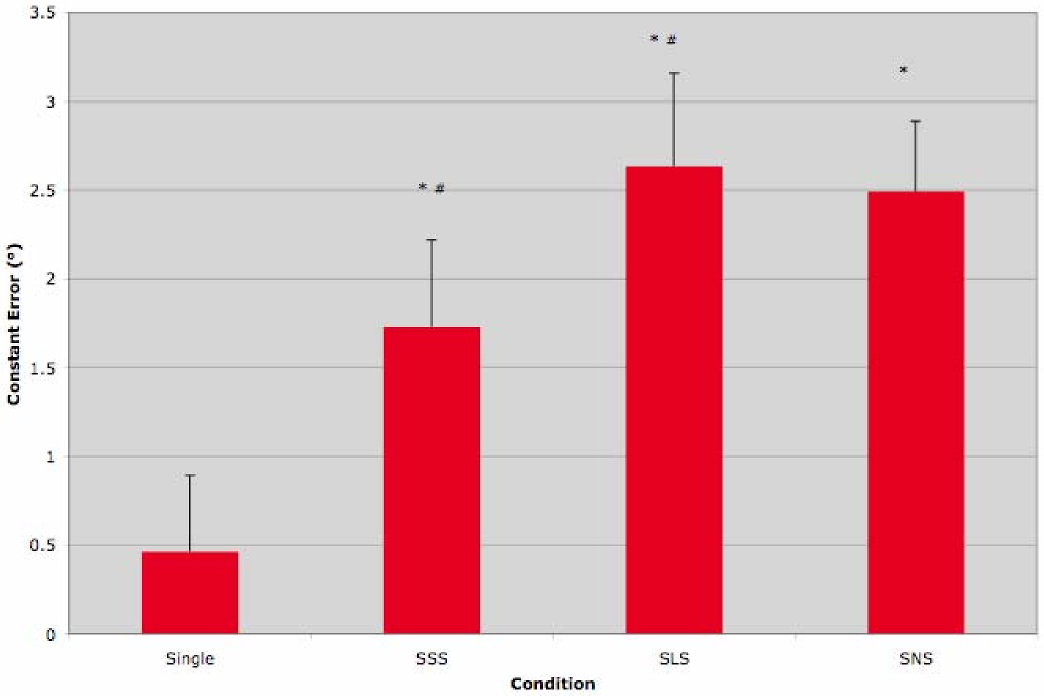

Figure 6. The mean constant error for the short single movements compared to the initial short movements of the three sequential conditions. The * indicates significantly different from the Single condition (p < .05). The # indicates significantly different from each other (p < .05). Standard error bars are also shown.

movement between the single (M = 183 ms) and sequential conditions (M= 187 ms), but the MT of the long movement was longer for the sequential condition (M = 255 ms) compared to the single trials (M = 219 ms). The effect of condition was significant for the long movement, $F_{(1,20)} = 12.6$, $P < .01$, $\eta^2=.39$.

DISCUSSION

The main goal of the experiment was to determine if the principles of motor program editing could be generalized to a three-movement sequence. Prior work with two-movement sequences had shown that performing a short distance movement following a longer distance movement resulted in overshooting the short movement relative to control conditions (22). Likewise, longer distance movements preceded by shorter movements resulted in undershooting of the longer movement. In the current experiment a longer distance movement was performed in between two shorter distance movements.

Evaluation of the Program Editing Hypothesis

Two main findings supported the expectations of the program-editing hypothesis (6). First, the long movement in the SLS sequence, which was preceded by the short movement, undershot the 60° goal by about 5% compared to the single trials. Secondly, the short movement at the end of the SLS sequence overshot the 20° goal to a greater extent compared to the same distance control conditions (SSS and SNS). Such findings support the Rosenbaum et al. data editing approach to motor programming (6). In their approach, when the force parameter value must be changed from one movement to the next, interference occurs resulting in overshooting or undershooting. The current findings also extend the findings of Rosenbaum et al. by demonstrating that the principles of program editing apply to movement sequences involving different hands, in addition to tasks using the fingers (6).

However, the surprising result was the overshooting was only noted in the nondominant hand, not the dominant hand. Prior work had shown that interference caused by changing the value of the program parameter in two-movement sequences was equal for both dominant and nondominant hands (22). It could be that the greater motoric experience with the dominant hand reduces the possible interference from a preceding movement compared to the nondominant hand. The lack of interference effects on the dominant hand in the experiment provided the main rationale for further work investigating the dominant hand exclusively.

A second expectation of the program-editing hypothesis was that movements would become more accurate and consistent when repeated during the same sequence. However, there was little support for this prediction. When participants repeated the same movement three times in the SSS sequence, greater overshooting was seen on the second and third movements relative to the first movement. Also there was no significant improvement in accuracy between the first and last movements of the SNS sequence. These findings do not support the Rosenbaum et al. parameter-editing approach to motor programming (6). In their approach, when the motor program parameter used on one movement is preserved for use on the next movement, performance is enhanced since program editing is not required. Taken together the results suggest that the program-editing hypothesis (6) can account for the interference when different movements are made in a sequence, but it cannot account for the lack of improvement when the same distance movements are repeated. However, the lack of improvement in the same distance conditions should be interpreted with caution since no retention or transfer tests were given.

Differences Between Single and Sequential Movements

Another surprising finding was that larger CEs were noted on the first movement of the sequences compared to the single movements. The short movement goal was overshot by 1-2° more than the single trials resulting in at least a doubling of the CE in all three sequences (Figure 6). The general overshooting of the short distance on the first sequential movement is probably due to interference generated by the random practice order of the three movement sequences. For example, even though there was only a 33% chance that the SLS sequence would be instructed on a given trial, overshooting of the short distance was found in all three sequences. During sequential practice, perhaps the participant was *prepared* to make the SLS sequence if requested. According to research on practice order and contextual interference, the interference here could be explained by the elaborative processing hypothesis (12-13). According to this hypothesis, movement errors are caused by interference between program parameters that are held concurrently in working memory. If both the short and long movement parameters are held in working memory at the same time, then the possibility for interference and movement biasing clearly exists. Evidently, this interference in working memory resulted in an overproduction of the force parameter for the short distance. However, it is unlikely that the contextual interference generated by the random practice would have a long-lasting negative effect on performance. In fact, greater levels of contextual interference have been shown to improve retention and transfer to similar motor skills. Therefore, the current results do not in any way negate or conflict with the numerous studies showing the advantages of random practice sequences compared to blocked practice on retention and transfer tests (1-2, 16-17, 23).

Implications for Other Theories of Motor Learning and Control

The current results showing that alternating short and long aiming movements causes greater errors compared to the repetition of the same movement also has implications for schema theory and for the modeling of the accuracy of rapid aiming movements. 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. The current findings suggest that variable practice conditions can cause increased performance errors compared to constant practice conditions, at least when movements occur within several seconds of one another. One might question how performance under such sequential movement conditions influences the recall and recognition schemata. According to schema theory, 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 (8-10, 19). Perhaps practicing aiming movements in a sequential manner could be considered a change in initial conditions over variable practice conditions where more time exists between movements. If this were the case, then unique recall and recognition schemata would be formed under these different practice conditions. Moreover, the increased performance errors caused by variable practice would be offset by the development of stronger schemata in the long run. Recent research has shown that practice of movement sequences can reduce the error in alternating movements compared to repeated conditions (6, 22), suggesting that the schemata are strengthened during this type of variable practice.

The current results also have implications for other models of motor control in addition to Rosenbaum et al's program editing model. For example, the impulse-timing model of motor control predicts that spatial movement accuracy decreases as movement distance increases and as movement time decreases in rapid, discrete aiming movements (13-14). According to the model, variability in force modulates spatial error. As longer distance movements are made while maintaining movement time, greater forces are required to move the limb. Greater forces are associated with greater variability in force, resulting in greater spatial error (11, 15, 20). The same holds true for the increased force required to produce reductions in movement time. However, the current results run counter to the predictions of the impulse-timing model since the constant errors are greater for the shorter distance movements compared to the longer distance movements. Clearly the interference from the longer distance movement affects the accuracy of the shorter distance movement in sequential actions. Therefore, the resulting accuracy of sequential aiming movements is not only due to the kinematic goals of the movement (i.e., distance and movement time), but also to the movement goals of the other movements in the sequence. It is clear that models of movement control based on discrete aiming movements cannot account for the principles of movement accuracy that emerge when sequential aiming movements are performed.

In summary, the findings of the current study suggest that spatial accuracy of rapid sequential movements decrease when the motor program parameters must be changed during the sequence. The results support Rosenbaum et al's program editing hypothesis, which can account for the errors noted in many common manual and sport skills. Perhaps future work can establish the underlying neurophysiological structures (e.g., the primary motor cortex, basal ganglia) responsible for the interference effects noted here.

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