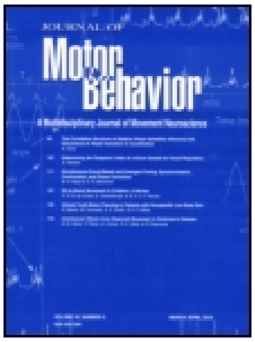

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Part–Whole Practice of Movement Sequences

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ABSTRACT. A 16-element movement sequence was taught under part–whole and whole-practice conditions. Participants (N = 18) produced a right-arm lever movement to sequentially presented target locations. The authors constructed part–whole practice by providing practice on only the 1st 8 elements on the 1st day of practice (100 repetitions of the 8-element sequence) and on all 16 elements on the 2nd day of practice (100 repetitions of the 16-element sequence). The whole-practice group practiced all 16 elements on both days (100 repetitions of the 16-element sequence per day). No differences in sequence structure or in movement duration of the 16-element sequence were noted on the retention test (Day 3). On transfer tests in which the 1st and last 8 elements were tested separately, however, the participants in the part–whole practice group performed more quickly than the participants in the whole-practice group, especially on the last 8 elements. Participants in the whole-practice group appeared to code the sequence so that it was relatively difficult to fully partition it into separate movements. Thus, on the transfer tests, there continued to be residual effects of the 8 elements that did not have to be produced but slowed down the rate of responding for the whole-practice group. That finding was not observed for the part–whole practice group.

Key words: hierarchical control, motor chunks, motor learning, movement structure, sequence learning

Understanding the processes involved in the fluent production of sequential movements, such as those involved in speech, handwriting, typing, drumming, or playing the piano, has been the object in much scientific inquiry for a number of theoretical and applied reasons. From a theoretical perspective, such an understanding is important because sequential movements are thought to be initially composed of a number of relatively independent elements that, through practice, are concatenated, consolidated, or otherwise organized into what appear to be a smaller number of sub-sequences (termed *motor chunks* by Verwey, 1994). As early as 1951, Lashley proposed that sequential actions are structured so that the order of the movement elements is determined independently of the nature of the movement elements (also see Keele, Jennings, Jones, Caulton, & Cohen; 1995; Klapp, 1995; Schmidt, 1975). In the 1980s and 1990s, Rosenbaum and his colleagues (e.g., Rosenbaum, Hindorff, & Munro, 1986; Rosenbaum, Kenny, & Derr, 1983; Rosenbaum & Saltzman, 1984; Rosenbaum, Saltzman, & Kingman, 1984) refined the notion of hierarchical control of movement sequences as a result of a series of experiments and theoretical models. In those models, hierarchical control of movement sequences is described in terms of an inverted tree or branch metaphor: That is, higher levels (nodes), which were thought to transmit sequence information, branch into lower levels where specific element and effector information is stored (also see Nissen & Bullemer, 1987, Povel & Collard, 1982). The internal representation of that information was thought to be retrieved, unpacked, parameterized, or edited (depending on the theoretical perspective) before execution so that the specific environmental demands could be met. The models seemed to account fairly well for (at least some of) the time delays between the execution of the discrete individual or grouped elements in the sequence, or both.

More recently, sequential movements have been viewed in terms of independent, perhaps parallel, processing mechanisms (e.g., Keele et al., 1995; Verwey, 2001; also see Schmidt, 1975): one processing mechanism that is responsible for planning and organizing the elements in the sequence, and the other responsible for the articulatory activities required to effect the planned action. Verwey, for example, proposed a cognitive mechanism that plans and

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represents the sequence and a motor mechanism that formulates the specific commands required to carry out the desired sequence. An interesting feature of Verwey's parallel, dual-processor model is the proposal that the cognitive- and motor-processing mechanisms are not only independent but also can operate in parallel. Thus, when a learned movement sequence is represented and executed as a series of sub-sequences (motor chunks), the planning of the next sub-sequence can be carried out while the current sub-sequence is being executed. Verwey made the interesting proposal that the execution of sub-sequences in multiple-sub-sequence movements is slower because the cognitive processor is required for high level sequence control, whereas in single-element or single-sub-sequence movements, the cognitive processor can be allocated to sequence execution. As a result, sequences that do not require that the cognitive processor be allocated to higher level processing should be executed more rapidly than the same elements in a more complex sequence. That model differs from other more serial dual-processor models (e.g., Keele et al., 1995; Klapp, 1995, 1996; Rosenbaum & Saltzman, 1984; Rosenbaum et al., 1984; Schmidt, 1975) in which the processing related to sequence organization is completed before the initiation of the movement sequence (i.e., preprogrammed) and therefore processing at one level is relatively independent of processing at other levels.

The study of sequential movements is also important from a practical standpoint because sequential movements make up a large percentage of our learned movement repertoire. Greater understanding of the processes involved in the performance and learning of movement sequences should lead to the design of more effective and efficient training procedures that will enable instructors to exploit the way performers structure, execute, and ultimately store movement sequences in memory. It is interesting that in many instances, instructors teach sequential movements by using one of several part–whole practice schemes (e.g., fractionation, segmentation, and simplification; Wightman & Lintern, 1985). Although on the surface, the results of much of the part–whole practice research do not appear to support the benefits of part–whole practice on learning (see Templet & Hebert, 2002, for a recent meta-analysis), the seemingly compelling logic is that one can best teach complex movement sequences by partitioning the whole sequence into smaller more manageable units that can later be combined to produce a consolidated sequence. A potential problem, however, has been that much of the research investigating part–whole practice notions, particularly in the motor skills domain, has not had a unifying theoretical basis on which to formulate experiments. In our opinion, the sequence learning literature has developed to the degree that it can provide strong guidance to research aimed at maximizing the effectiveness, flexibility, and efficiency of sequence learning.

Therefore, our primary purpose in the present experiment was to revisit the issue of part–whole training of movement sequences by using the findings and predictions from the sequence learning literature to guide the investigation. In the present research, we used a continuous serial reaction time task[1] (see Park & Shea, 2002) composed of 16 elements, in which participants initially had to react to the visually presented targets by making an arm movement much as they would do in a choice reaction time paradigm. Because the stimuli and targets were presented in a repeated sequence, however, participants began to anticipate the upcoming stimuli and target—thus reducing the time required to respond. Because more and more of the sequence was learned, the time required to move from one target to the next (element duration) was further reduced. With additional practice, participants became less reactive to the visually presented targets because they could anticipate the upcoming target in the sequence. That achievement resulted in an increasingly more rapid and fluid sequence production. In our previous research (Park & Shea, 2002) in which that task was used, participants were found to chunk or package two or more elements together so that the elements appeared to be executed as relatively independent sub-sequences. Generally, those sub-sequences have been operationally defined as a relatively long movement time to a target (beginning of sub-sequence) followed by relatively short movement times to one or more of the following targets (see Nissen & Bullemer, 1987, Povel & Collard, 1982; Verwey, 1994). The delay before the first item in a sub-sequence was thought to occur because the sub-sequence had to be retrieved, programmed, or otherwise readied for execution. Subsequent elements in the sub-sequence were produced more rapidly than the first because processing related to their production was completed during the initial interval.

In this experiment, as in a number of other experiments involving repeated sequences (e.g., Keele et al., 1995), we also had participants perform a few blocks involving randomly presented elements. We followed that procedure to determine whether differences arise between groups in terms of general performance capabilities unrelated to the repeated sequences and to determine the extent to which performance and learning are differentially incremented by the practice schemes involving the repeated sequence.

To study part–whole practice, we arbitrarily decomposed a 16-element sequence into two 8-element parts. The first 8 elements were termed *Sequence A*, and the second 8 elements were termed *Sequence B*. Thus, the whole sequence was labeled *Sequence AB*. On the 1st day of practice, one group practiced only Sequence A (part-sequence practice) and the other practiced Sequence AB (whole-sequence practice). On the 2nd day of practice, both groups practiced Sequence AB. On the 3rd day, all participants completed a retention test on Sequence AB and two transfer tests. The transfer tests involved producing Sequences A and B independently (tests counterbalanced). On the basis of the findings reported in past literature on part–whole practice, we hypothesized a small (e.g., Ash & Holding, 1990; Watters, 1992), if any (e.g., Knapp & Dixon, 1952; Lersten, 1968), advantage for the part-practice group on the retention test.

However, we hypothesized that part–whole practice would accrue additional subtle advantages that are not typically assessed in traditional part–whole practice research but are predicted in the sequence learning literature. Specifically, we anticipated that because of the way practice was structured, the part–whole practice group would be more effective than the whole-practice group in producing the parts of a sequence. Although the difference might not be as apparent when participants produced Sequence A, because the whole sequence could be prepared with the final elements simply aborted or edited out (Rosenbaum & Saltzman, 1984), performance on Sequence B should be especially informative. Evidence that the part–whole practice participants could execute Sequence B more rapidly than could the whole-practice participants, even though they received only 1 rather than 2 days of practice on Sequence B, would suggest that the 8-element sequences had retained their identity even though they appeared to have been effectively concatenated during the 2nd day of practice.

In addition, how quickly Sequences A and B could be produced in comparison with the respective elements in Sequence AB would be informative. Verwey (2001) argued that the processing of later parts of a sequence can occur during the execution of the earlier parts when the cognitive processor is allocated to higher order sequence processing. The simultaneous processing must occur so that sub-sequences can be effectively concatenated, but it results in a general slowing down of the sub-sequences because the cognitive and motor processors are allocated to different aspects of the task. However, if Sequences A and B are completed more rapidly when produced separately than when combined, without specific increases or decreases in sub-sequence production, then the residual effects of the other sub-sequences would have been eliminated. Verwey would argue in that case that the cognitive processor was reallocated to response execution processing. Alternatively, if only the first element in a sub-sequence is produced more rapidly in the shorter sequences, notions related to resource load or retrieval, or both, are implicated as the reason that the longer sequences are produced more slowly.

Method

Participants

Undergraduate students (N = 18) participated in the experiment for course credit. They had no prior experience with the experimental task and were not aware of our specific purpose in the study. All participants were right-hand dominant, as determined by self-report before the experiment. Informed consent was obtained before participation in the experiment.

Apparatus

The apparatus consisted of a horizontal manipulandum (42 cm long) affixed at the proximal end to a near-frictionless vertical axle. The axle, which rotated freely in ball-bearing supports, allowed the manipulandum to move in the horizontal plane over the table surface. Near the distal end of the manipulandum, a vertical handle was attached. The position of the handle could be adjusted so that participants could comfortably grasp the handle (palm vertical) when they rested their forearm on the lever, with the elbow aligned over the axis of rotation. A potentiometer attached to the lower end of the axle monitored (100 Hz) the horizontal movement of the manipulandum. We used a custom data-collection program to process the potentiometer data and time the various intervals during data collection. We used the processed data to provide task information and online feedback on a 21-in. color monitor, and we stored the data for later analysis.

Procedure

After completing the informed consent, participants were seated in a chair, facing a computer screen. The position of the handle on the manipulandum was adjusted so that the participants' elbow was directly over the axis of rotation when they gripped the handle, and the height of the chair was adjusted so that their lower arm could comfortably rest on the top surface of the manipulandum.

Instructions were then given on how to perform the task. To begin each trial, participants were told to move the cursor displayed on the computer monitor (which represented the position of the manipulandum) below the horizontal line near the bottom of the screen (see Figure 1). That position was described as the start position (0°). Participants were informed that as they moved the manipulandum away from their body (elbow extension), the cursor would move up the screen and that movement toward themselves (elbow flexion) would cause the cursor to move down the screen. At the start position, the participants' lower arm was at approximately an 80° angle to the upper arm. When the start position was achieved, four target (rectangles) positions were displayed on the computer monitor. The height of the targets represented 2° of elbow extension (or flexion), with the centers of the targets representing lever positions of 20°, 40°, 60°, and 80° (see Figure 1) from the start position. The targets were referred to as *Targets 1–4*, respectively. After a random foreperiod (1 to 5 s in 0.5-s intervals), a start tone was presented, and the first target in the sequence was illuminated. Thus, the presentation of the four target positions served as a warning that the trial was about to begin, and the start tone and illumination of the first target provided the cues to begin. Participants were instructed to move the cursor (manipulandum) as quickly as possible to the target. When the participants hit the target (the cursor crossed the edge of the target), the illumination was turned off and the next target was immediately illuminated until the sequence was completed. Participants were instructed to move the manipulandum from one target to the next as quickly and smoothly as possible. If the participants missed a target, then the target remained illuminated until the participants returned the cursor to the target position. When participants had completed a sequence, they received a stop tone, and

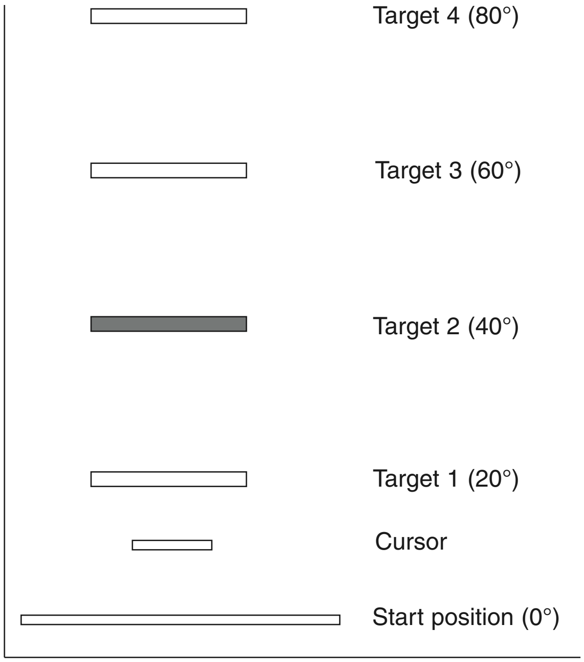

FIGURE 1. Illustration of the screen display during a trial. In this example, the cursor, which indicates the position of the manipulandum, is 10° above the baseline (0°) and Target 2 (40°) is illuminated. The labels to the right were not displayed on the screen and are presented here only to clarify the labels used for the various positions displayed.

the total time required to complete the sequence was displayed. Between repetitions, participants were instructed to wait at the start position for the targets to appear and to begin their movement when the start tone was presented and the first target was illuminated. Within a block, repetitions were begun at 30-s intervals, with an additional 30-s rest interval between blocks.

Participants were randomly assigned to either a part–whole or a whole-practice group, which differed in terms of the number of elements (8 or 16) in the sequence that were practiced on Day 1. To create the required sequences, we constructed two 8-element sequences. One sequence (A) consisted of Targets 2, 3, 4, 3, 2, 3, 2, and 1; the other (B) consisted of Targets 2, 3, 2, 3, 4, 3, 2, and 1. Targets 1–4 corresponded to 20°, 40°, 60°, and 80° from the start position, respectively (see Figures 1 and 2). On Day 1, participants in the part–whole practice group were exposed only to Sequence A (8 elements). The participants in the whole-practice group responded to Sequences A and B, which were combined to form one 16-element sequence (AB). On Day 2, all participants practiced the combined 16-target Sequence AB. Each day of practice (Days 1 and 2) consisted of 1 random block (10 repetitions of random sequences) and 10 repeated-sequence blocks (10 repetitions of the assigned sequence per block). Participants were not provided any advance information about the sequences.

A retention test, two transfer tests, and a random sequence test were conducted on Day 3. Sequence AB (16-target sequence), which was practiced by the part–whole

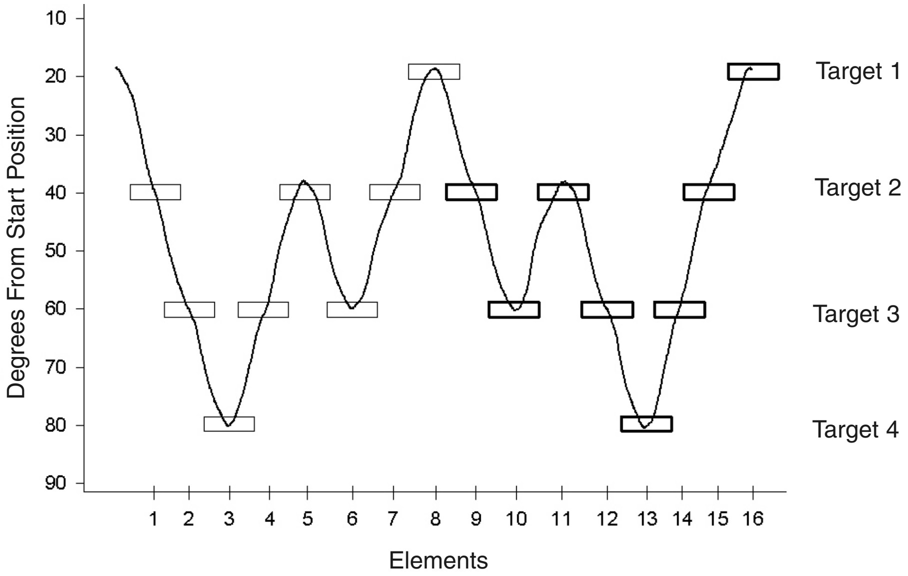

FIGURE 2. Illustration of Sequence AB (16 elements). Targets (right axis) are presented in terms of lever position (left axis), with a typical movement pattern overlaid. Note that Sequence AB included the 8 elements in Sequence A (not bold) and the 8 elements in Sequence B (bold).

practice group on Day 2 and by the whole-practice group on Days 1 and 2, was used for the retention test. Thus, the retention test task was identical to that used in practice, except that the total time required to complete the sequence was not displayed on completion of the sequence. After completing the retention test, participants performed two transfer tests in which they were asked to independently produce Sequences A and B. Our reason for conducting the transfer tests was to examine the ability of the practice groups to effectively decompose the 16-target sequence into two 8-target sequences. The order of those two transfer tests was counterbalanced. After completing the transfer tests, a random sequence test was administered. That test was identical to the random blocks that were administered at the beginning of each day of practice. The random blocks at the beginning of Days 1 and 2 of practice and during the test phase on Day 3 were used as a method of determining general improvement in performance from specific improvements related to learning the repeated sequences.

Results

The dependent variable for all analyses was element duration. Element duration was computed as the elapsed time from hitting the previous target to hitting the current target. A preliminary analysis was conducted on the random sequence blocks (indicated as R on Figure 3) conducted on each day. Performance on those blocks did not appear to differ across practice groups but was consistently elevated in comparison with performance on the repeated blocks (Blocks 1–10). The analysis failed to indicate a difference between the part–whole and whole-practice groups but did indicate decreased element duration in random sequence performance from Day 1 to Day 2, with no further decreases on Day 3. The Practice Group × Block interaction was not significant. We used the random blocks as a reference to separate the general learning effects associated with the task and how best to move the lever from movement advantages associated with learning the repeated sequence. The performance on the random sequence blocks confirmed that there were no general performance differences between the part–whole and the whole-practice groups.

To analyze the acquisition performance on the repeated sequences, we analyzed mean element duration in a 2 (practice group: part–whole or whole) × 2 (day: 1 and 2) × 10 (block: 1–10) analysis of variance (ANOVA) with repeated measures on day and block. Retention performance was analyzed in a 2 (practice group: part–whole or whole) × 16 (element: 1–16) ANOVA with repeated measures on elements.

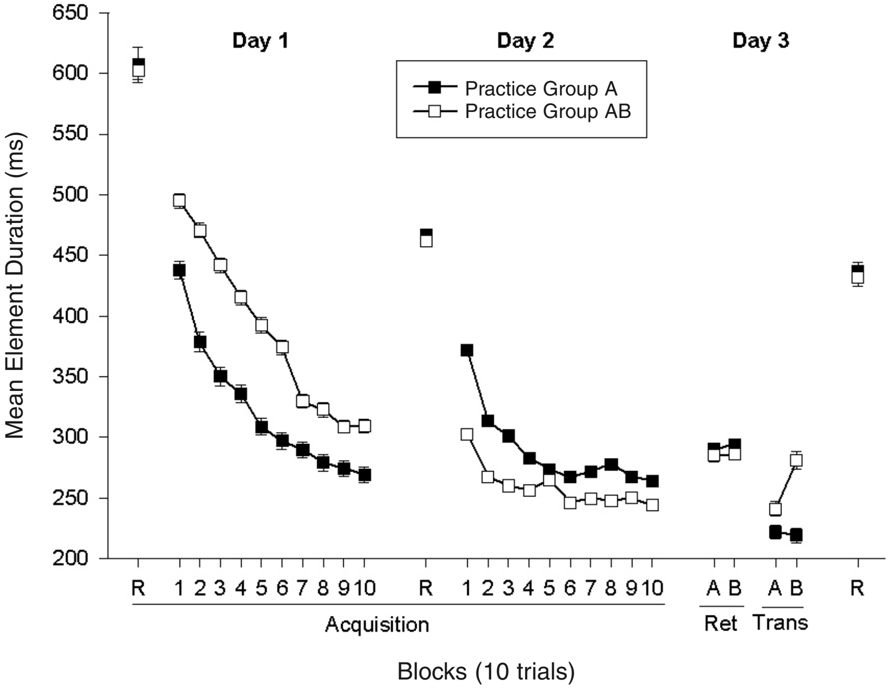

FIGURE 3. Mean element duration during acquisition (Days 1 and 2), retention (Ret), and transfer (Trans). On each day of acquisition, a block involving random sequences (R) was presented before the 10 blocks involving the repeated sequence (Blocks 1–10). After participants completed the transfer tests, another random block was presented. Note that although the retention test required the production of Sequence AB, we present mean element duration separately for the first and the last eight elements to facilitate comparison with transfer performance.

Transfer performance was analyzed in separate 2 (practice group: part–whole or whole) × 8 (element: 1–8) ANOVAs with repeated measures on element. Mean element duration is displayed by practice group across days and blocks in Figure 3. Note that although the retention test involved Sequence AB, performances of the first and last 8 elements are displayed in Figure 3. We show those data to facilitate comparison with performance on the transfer tests. Mean element duration on the retention (top panel) and transfer (bottom panel) tests for each element are displayed in Figure 4.

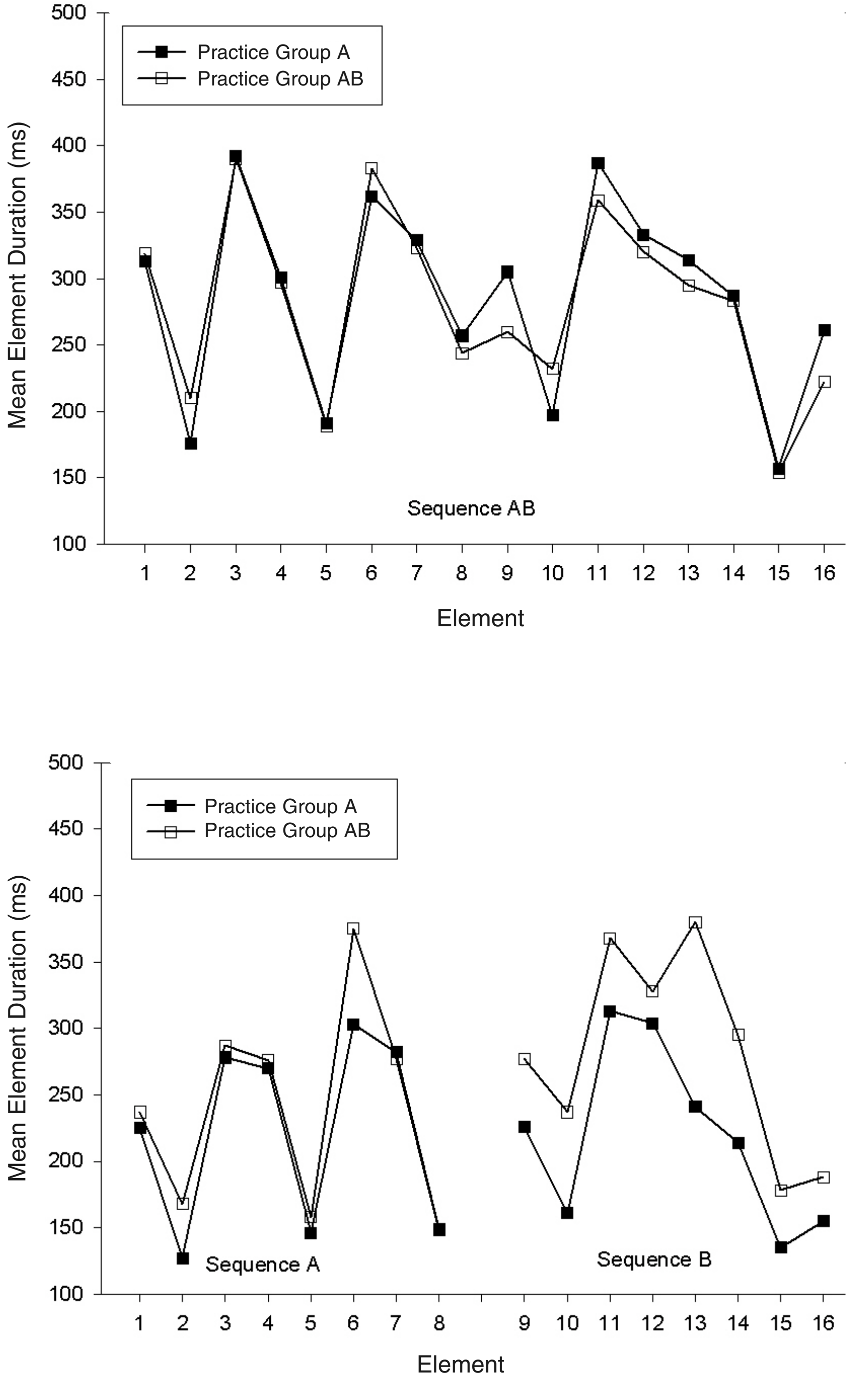

FIGURE 4. Mean element duration time for Sequence AB during retention (**top**) and for Sequences A and B separately during transfer (**bottom**), by element (serial position) and by practice group.

Acquisition

Participants in both practice groups improved their performance on the repeated sequences (see Figure 3, Blocks 1–10) over practice; the largest improvement was across blocks on Day 1. Most interesting, mean element duration on Day 1 was shorter for the part–whole practice group than for the whole-practice group, probably because of differences in the number of elements in the sequences that were practiced. On Day 2, both groups practiced Sequence AB, and the reverse was found: Participants in the whole-practice group performed the sequence somewhat faster (i.e., shorter element duration) than did participants in the part–whole practice group. A main effect of practice group was not detected, $F(1, 140) < 1$, but main effects of day, $F(1, 14) = 16.57$, $p < .01$, and block, $F(9, 126) = 46.02$, $p < .01$, were found. In addition, the Practice Group × Block, $F(1, 14) = 7.26$, $p < .05$, the Day × Block, $F(9, 126) = 14.49$, $p < .01$, and the Practice Group × Day × Block, $F(9, 126) = 2.53$, $p < .05$, interactions were significant.

Retention

Participants in the two practice groups performed similarly on the retention test both in terms of element duration (Figure 3) and in terms of the way in which the sequence was structured (Figure 4, top). The main effect of practice group, $F(1, 14) < 1$, and the Practice Group × Element interaction, $F(15, 210) < 1$, were not significant. The main effect of element, $F(15, 210) = 32.25$, $p < .05$, was significant. Duncan's new multiple range test indicated that Elements 3, 6, and 11 were performed more slowly (i.e., longer element duration) than were all other elements.

Transfer

On the transfer tests, participants were asked to produce the first eight elements (Sequence A) and last eight elements (Sequence B) in separate tests. Performance on Sequence A was similar for both the part–whole practice ($M = 222$ ms, $SE = 11$)[2] and the whole-practice ($M = 241$ ms, $SE = 15$) groups. The main effect of practice group, $F(1, 14) < 1$, and the Practice Group × Element interaction, $F(7, 98) < 1$, were not significant. The main effect of elements, $F(7, 98) = 11.82$, $p < .01$, was significant; element duration for Element 6 was longer than were the durations of all other elements.

When tested on Sequence B, however, participants in the part–whole practice group ($M = 219$, $SE = 12$) performed the sequence more quickly than did participants in the whole-practice group ($M = 281$, $SE = 17$). The main effects of practice group, $F(1, 14) = 2.97$, $p < .05$, and element, $F(7, 98) = 19.16$, $p < .01$, were significant. The multiple range test on element indicated that Element 11 was performed most slowly (longer element duration) in the 16-element sequence on the retention test but that Elements 12 and 13 were also performed more slowly than were all other elements in the sequence. Although there appeared to be some differences in the structure of Sequence B between the two practice groups, the Practice Group × Element interaction, $F(7, 98) = 1.31$, $p > .05$, was not significant.

Retention and Transfer Comparisons

Most interesting, average element duration for Sequences A and B appeared to be shorter than that of the 16-element sequence (Sequence AB). The difference can be clearly seen in Figure 5, which shows the contrast between retention and transfer for Practice Groups A (top) and AB (bottom). To investigate that finding, we conducted a Practice Group × Sequence Length ANOVA on the retention and transfer sequences for each practice group. The analysis of the part–whole practice group (Figure 5, top) indicated a main effect of sequence length for Sequence A, $F(1, 14) = 8.4$, $p < .01$, and for Sequence B, $F(1, 14) = 4.92$, $p < .05$. Although the main effects of element for Sequences A and B were significant, $F\text{s}(7, 98) = 27.16$ and 24.70, $p\text{s} < .01$, respectively, the Sequence Length × Element interactions were not significant, $F\text{s}(7, 98) = 1.36$ and 1.09, $p\text{s} > .05$, respectively, for Sequences A and B.

In the analysis of the whole-practice group (Figure 5, bottom), a main effect of sequence length was detected for Sequence A but not for Sequence B, $F(1, 14) = 3.09$, $p < .05$, and $F(1, 14) = 0.89$, $p > .05$, respectively. The elements in Sequence A were executed more rapidly in the 8-element transfer test than in the 16-element retention test. The main effects of element, $F\text{s}(7, 98) = 33.47$ and 21.67, $p\text{s} < .01$, for Sequences A and B, respectively, were significant. Although the movement structure for Sequence A appeared somewhat different on the transfer test than on the retention test, the Sequence Length × Element interaction, $F(7, 98) = 1.88$, $p = .08$, was nonsignificant. The Sequence Length × Element interaction was also nonsignificant for Sequence B, $F(7, 98) = 1.47$, $p > .05$.

Discussion

Our primary objective in the present experiment was to determine the extent to which part–whole and whole-sequence practice affect the sequence structure and production speed of a 16-element repeated movement sequence. Random sequence blocks were inserted at the beginning of each day of practice and at the end of the retention and transfer sessions. Random sequence blocks have been used (e.g., Keele et al., 1995) as a way of separating general task learning effects from the effects of information learned about the repeated sequence. Differences between practice groups on general task learning would be interpreted quite differently from differences in the manner in which sequence information was learned and structured. In the present experiment, random sequence performance improved from the 1st day of practice to the 2nd but did not show additional improvements on Day 3. More important, there were no differences between practice groups on the random blocks, suggesting that the practice manipulation did not result in differential general learning benefits. Thus, differences in acquisition, retention, and transfer perfor-

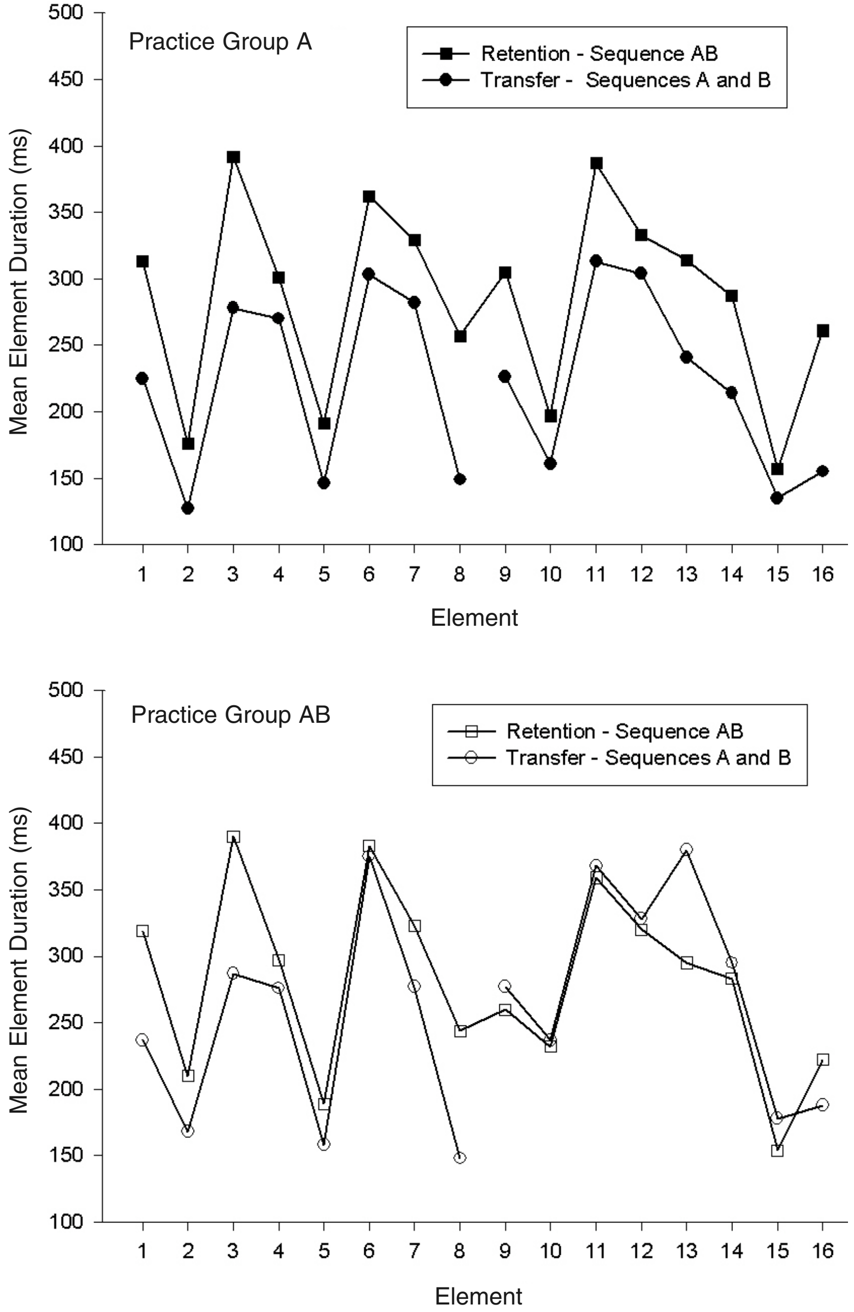

FIGURE 5. Mean element duration for the Practice Groups A (**top**) and AB (**bottom**) on the retention and transfer tests.

mance on the repeated sequences, if any, can be attributed to differences in the manner in which the sequence information was learned and structured.

The retention test administered approximately 24 hr after the end of practice was used as a measure of learning. We used transfer tests in which participants were asked to produce only the first or second half of the 16-element sequence to determine the degree to which the two 8-element sequences included in the 16-element sequence could be produced independently and to assess potential costs associated with producing the sequences of different lengths. On Day 1, mean element duration of Practice Group A was shorter than that of Practice Group AB. Presumably, the demands of learning the 8-element sequence were less than those of the 16-element sequence, allowing participants to better anticipate the upcoming stimulus and more effectively structure the movement pattern when the sequences were shorter. On Day 2, both groups practiced Sequence AB, and that advantage was lost. Although the difference between the two groups on mean element duration narrowed over practice, small differences in favor of Practice Group AB persisted at the end of practice. On the retention test, however, which was conducted approximately 24 hr after the completion of practice, participants in Practice Groups A and AB performed similarly. That similarity was observed not only in terms of mean element duration but also in terms of the sequence structure. In fact, the patterns of element durations across elements were nearly identical for the two groups (see Figure 4, top).

The movement structure on the retention test was particularly interesting from the standpoint of the transition from Sequence A to Sequence B. We anticipated that participants might structure (partition into sub-sequences and motor chunks) the movement sequence differently depending on whether they received part- (Sequence A) or whole- (Sequence AB) sequence practice on Day 1. On the basis of past experience with Sequence AB (Park & Shea, 2002), we anticipated that participants in Practice Group AB would structure the sequence so that Elements 3, 6, and 11 would be performed more slowly than all other elements. Those subtle delays in responding, followed by a sequence of more rapidly produced elements, have been interpreted as indicators marking the division of the whole sequence into sub-sequences (e.g., Nissen & Bullemer, 1987; Povel & Collard, 1982) or motor chunks (Sternberg, Knoll, & Turock, 1990; Verwey, 1996; Verwey & Dronkert, 1996). According to that viewpoint, additional time is required to retrieve, unpack, parameterize, or otherwise ready the upcoming sub-sequence for execution. Subsequent elements in the sub-sequence are performed more rapidly because they are not encumbered with the additional retrieval and processing delays. The result is a more rapid and fluent but yet structured production of the sequence. Although we anticipated that pattern of responding for Practice Group AB, we hypothesized that the movement sequence produced by the participants in Practice Group A might be structured differently as a result of practicing only Sequence A on Day 1. Verwey (1994), for example, demonstrated that short delays introduced between elements early in practice changed the way the sequence was structured and that the structure persisted when the delays were eliminated later in practice. In short, we anticipated that practicing Sequence A alone before practicing Sequence AB might result in a more pronounced demarcation between the first and last 8 elements—similar to that seen for the beginning of sub-sequences. That type of sequence structure was not observed because both groups structured the sequence similarly; that is, durations for Elements 3, 6, and 11 were elevated in comparison with those of the other elements. The sequence structures for both practice groups were similar to that observed by Park and Shea (2002) for the same sequence and task. The transition from Sequence A to Sequence B for the part–whole practice group, however, was not entirely seamless. There was a subtle increase in the time required to produce the first element in Sequence B (Element 9). Although the increase was not enough to cause a significant Practice Group × Element interaction, the increase suggests that Sequences A and B might have been more loosely organized for the participants in Practice Group A than for those in Practice Group AB.

After completing the retention test, we conducted two transfer tests to examine participants' ability to independently produce Sequences A and B. We initially hypothesized that the participants in Practice Group A might demonstrate an advantage in producing the two 8-element sequences because they had some experience in producing Sequence A independently before practicing the combined Sequence AB. That advantage could occur if participants structure the longer sequence differently depending on whether they initially receive part- or whole-sequence practice. However, given the similarity in the way participants structured the 16-element sequence on the retention test, it seemed unlikely that the practice groups would differentially respond to the 8-element sequences. In addition, we were interested in comparing the costs, if any, associated with producing the 16-element sequence with the costs of the 8-element sequences. Typically the elements or sub-sequences in shorter sequences are produced more rapidly than are those in longer sequences (sequence length effect; see Sternberg, Monsell, Knoll, & Wright, 1978; Verwey, 1994, 1996). The difference is believed to be caused by one or both of two factors that are introduced in longer sequences. First, the production of longer sequences might be slowed because of increased competition for limited memory, processing, or attentional resources. Second, the concurrent advance processing of upcoming sub-sequences and production of ongoing sub-sequences are thought to smooth out the transition from one sub-sequence to the next but also to generally slow the production of the ongoing sub-sequence. Verwey argued that the cause of the slowing observed in longer sequences is that the cognitive processor is allocated to higher order processing and thus is not contributing to the speed with which the motor processing is completed. The latter hypothesis can be differentiated from the former by whether the delays are evenly distributed throughout the sequence or are isolated to the earlier portions of the sub-sequences. That is, concurrent processing should result in a general slowing of all elements in the sequence, whereas resource limitations should be isolated to the first element of the sub-sequences. Thus, the more rapid production of the elements in Sequences A, B, or both, than the same elements in Sequence AB would indicate that the shorter sequences were produced independently—unencumbered by processing demands associated with the other half of the whole 16-element sequence.

Participants in Practice Groups A (–68 ms) and AB (–44 ms) produced Sequence A on the transfer test significantly faster than they did when the same elements were included in Sequence AB (retention test). Although that finding represents what has been referred to as the sequence length effect (e.g., Sternberg et al., 1978), the increased speed suggests that both groups were able to produce the first eight elements without the costs associated with the additional elements in the longer sequence. However, the results from the transfer test on Sequence B suggest that that interpretation might not be quite so straightforward. Participants in Practice Group AB were able to produce Sequence A substantially faster than they did the same elements combined in Sequence AB, but they were unable to produce Sequence B alone any faster than Sequence AB (–5 ms). That was not the case for participants in Practice Group A, who were able to produce both Sequences A and B alone more rapidly than the combined Sequence AB (–75 ms).

The finding that participants in Practice Group AB were able to produce Sequence A, but not Sequence B, faster than the same elements combined in Sequence AB, is particularly noteworthy. That result is consistent with the notion that to produce Sequence B, participants in Practice Group AB had to load the entire 16-element sequence and thus incurred costs associated with the initial 8 elements. However, that proposition does not seem compatible with the finding that Sequence A was produced more rapidly than were the same elements in Sequence AB. The conflict could be resolved if one assumes that participants can effectively truncate elements at the end but not at the beginning of a sequence. Elements and sub-sequences at the beginning of a series might provide important cues and context necessary for the readying of later sub-sequences and thus might be difficult to edit out before execution. In some ways, that explanation might be analogous to the waiter who has memorized the nightly menu. It is no problem for him to fluently present the first part of the menu and stop at any point, but it is difficult to start in the middle without going back through beginning of the list. Similarly, an individual can easily name the first numeral in his or her phone number without much hesitation, but to recall a number later in the sequence, the individual must silently work through the preceding elements before specifying the number requested. Rosenbaum and his colleagues (Rosenbaum, Inhoff, & Gordon, 1984; Rosenbaum & Saltzman, 1984) proposed a hierarchical editor model whereby learned movement sequences can be edited with some limitations before execution. The present data suggest that the cost associated with the editing process is less when the latter part of the sequence is truncated than when the beginning is deleted. The fact that participants in Practice Group A did not seem to accrue those costs suggests that they were able to independently produce either Sequence A or B without incurring the cost associated with loading the entire sequence.

The present findings also have implications for the debate between resource (e.g., Kahneman, 1973), serial processing (e.g., Keele et al., 1995; also see Schmidt, 1975), and parallel processing (e.g., Verwey, 1994) models that have been used to account for delays in processing of longer as opposed to shorter sequences (sequence length effect). In resource models, the delay in processing of longer sequences is explained as the result of “tying up” one or more sets of processing, memory, or attentional resources needed to produce the movement sequence. The tying up should result in additional delays in the processing of the first element of sub-sequences but have little effect on the other elements in the sub-sequences. Similarly, according to the serial processing explanation, the first element, but not the others in a sub-sequence, is produced more slowly because of the additional time required to retrieve, compile, or otherwise ready the next sub-sequence. Alternatively, in his parallel processing account, Verwey (1999) proposed that the advance processing of one sub-sequence slows the production of the current sub-sequence because only the motor processor is allocated to response production. In multiple-sub-sequence movements, the cognitive processor must be allocated to the higher order processing involved in the organization of the sub-sequences. The predictions of the resource, serial processing, and parallel processing models are generally the same—slower production of longer than shorter sequences. However, the resource and serial processing models predict delays in the first element of the sub-sequences, and Verwey’s parallel processing model predicts more general delays across the sequences. The present data were consistent with the predictions in Verwey’s model because delays in producing the 16-element sequence in comparison with the 8-element sequences appeared to be manifested throughout the sequence rather than isolated to the earlier portions of the sub-sequences.

It is also interesting to note that from a part–whole training perspective, Practice Condition A (part–whole practice) could be considered more efficient than Practice Condition AB (whole practice). More efficient training results when the costs in terms of money, time, effort, and potential injury, for example, are reduced. When practice effectiveness is equal across practice conditions, as was the case in the retention test in the present experiment, practice efficiency becomes a key consideration in deciding on a practice scheme. In the present experiment, participants in Practice Group A were required to respond to 25% fewer targets during acquisition than were participants in Practice Group AB, without a loss in terms of learning effectiveness. Indeed, the finding that participants in Practice Group A could effectively produce not only the whole sequence (AB) but also the individual components (A or B) adds to the benefits of the part–whole practice condition.

In summary, part–whole practice failed to result in advantages or disadvantages in comparison with whole practice in terms of learning the whole (16-element) movement sequence. However, part–whole practice resulted in more effective transfer to Sequence B (last 8-elements) but not to Sequence A (first 8-elements) than did whole practice. That finding is important theoretically because it demonstrates that the whole-practice group was able to truncate elements at the end, but not the beginning, of the learned sequence without incurring processing costs associated with the whole sequence. Part–whole practice allowed participants to effectively eliminate either the first or the last half of the response without incurring processing costs associated with longer sequences.

NOTES

1. The labels *serial reaction time task* and *SRT* are commonly used in describing keying sequences that require participants to cycle through a repeated response sequence. The difference between the task used in this experiment and that used in typical SRT experiments is that the present participants used a single effector rather than different effectors (fingers) to respond to the stimuli. Thus, we refer to the present task as a *continuous SRT task* and would refer to the more typical version as a *discrete SRT task*.

2. Mean is denoted by *M* and standard error of the mean by *SE*.

REFERENCES

Ash, D. W., & Holding, D. H. (1990). Backward versus forward chaining in the acquisition of a keyboard skill. *Human Factors, 32,* 139–146.

Kahneman, D. (1973). *Attention and effort.* Englewood Cliffs, NJ: Prentice Hall.

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

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

Knapp, C. G., & Dixon, W. R. (1952). Learning to juggle II: A study of whole and part methods. *Research Quarterly, 23,* 398–401.

Lashley, K. S. (1951). The problem of serial order in behavior. In L. A. Jeffress (Ed.), *Cerebral mechanisms in behavior* (pp. 112–136). New York: Wiley.

Lersten, K. C. (1968). Transfer of movement components in a motor learning task. *Research Quarterly, 39,* 575–581.

Nissen, M. J., & Bullemer, P. (1987). Attentional requirements of learning: Evidence from performance measures. *Cognitive Psychology, 19,* 1–12.

Park, J-H., & Shea, C. H. (2002). *Sequence learning: Response structure and effector transfer*. Manuscript submitted for publication.

Povel, D., & Collard, R. (1982). Structural factors in patterned finger tapping. *Acta Psychologica, 52,* 107–123.

Rosenbaum, D. A., Hindorff, V., & Munro, E. M. (1986). Programming of rapid finger sequences. In H. Heuer & C. Fromm (Eds.), *Generation and modulation of action patterns* (pp. 64–71). Berlin: Springer-Verlag.

Rosenbaum, D. A., Inhoff, A. W., & Gordon, A. M. (1984). Choosing between movement sequences: A hierarchical editor. *Journal of Experimental Psychology: General, 113,* 372–393.

Rosenbaum, D. A., Kenny, S., & Derr, M. A. (1983). Hierarchical control of rapid movement sequences. *Journal of Experimental Psychology: Human Perception and Performance, 9,* 86–102.

Rosenbaum, D. A., & Saltzman, E. (1984). A motor-program editor. In W. Prinz & A. Sanders (Eds.), *Cognition and motor processes* (pp. 51–61). New York: Springer-Verlag.

Rosenbaum, D. A., Saltzman, E., & Kingman, A. (1984). Choosing between movement sequences. In S. Kornblum & J. Requin (Eds.), *Preparatory states and processes* (pp. 119–134). Hillsdale, NJ: Erlbaum.

Schmidt, R. A. (1975). A schema theory of discrete motor skill learning. *Psychological Review*, *82,* 225–260.

Sternberg, S., Knoll, R. L., & Turock, D. L. (1990). Hierarchical control in the execution of action sequences: Tests of two invariance properties. In M. Jeanerod (Ed.), *Attention and performance XIII* (pp. 3–55). Hillsdale; NJ: Erlbaum.

Sternberg, S., Monsell, S., Knoll, R. L., & Wright, C. E. (1978). The latency and duration of rapid movement sequences: Comparisons of speech and typewriting. In G. E. Stelmach (Ed.), *Information processing in motor control and learning* (pp. 117–152). New York: Academic Press.

Templet, E., & Hebert, E. (2002, March). *A meta-analysis of part-whole research on motor skill acquisition and learning*. Paper presented at the annual meeting of the American Association of Health, Physical Education, Recreation, and Dance, San Diego, CA.

Verwey, W. B. (1994). Evidence for the development of concurrent processing in a sequential key pressing task. *Acta Psychologica, 85,* 245–262.

Verwey, W. B. (1996). Buffer loading and chunking in sequential keypressing. *Journal of Experimental Psychology: Human Perception, and Performance, 22,* 544–562.

Verwey, W. B. (1999). Evidence for a multistage model of practice in a sequential movement task. *Journal of Experimental Psychology: Human Perception and Performance, 25,* 1693–1708.

Verwey, W. B. (2001). Concatenating familiar movement sequences: The versatile cognitive processor. *Acta Psychologica, 106,* 69–95.

Verwey, W. B., & Dronkert, Y. (1996). Practicing a structured continuous key pressing task; Motor chunking or rhythm consolidation? *Journal of Motor Behavior, 28,* 71–79.

Watters, R. G. (1992). Retention of human sequenced behavior following forward chaining, backward chaining, and whole task training procedures. *Journal of Human Movement Studies, 22,* 117–129.

Wightman, D. C., & Lintern, G. (1985). Part-task training strategies for tracking and manual control. *Human Factors, 27,* 267–283.

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