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The influence of movement segment difficulty on movements with two-stroke sequence

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Abstract Arm movements in the horizontal plane consisting of two segments were examined to determine whether the difficulty of the second segment influenced the kinematic characteristics of the first segment. The direction of the first segment was an elbow extension movement away from the trunk and remained constant throughout the experiment. The direction of the second segment varied between forearm extension and flexion movements. Based on Fitts' law, two different indexes of difficulty (ID) of the second segment were utilized by changing target size and movement amplitude. The effects of changing ID were examined for two different movement amplitudes. All movements were single-joint movements employing elbow flexion/extension and were recorded by an *x-y* digitizer. Variations in the ID of the second segment produced context-dependent kinematic changes in the performance of the initial segment. Movement duration increased when the ID was increased by reducing target size for both extension-extension sequence and extension-flexion sequences. Peak velocity also decreased for higher ID targets in the extension-flexion sequence. However, there was an interaction between the ID and movement amplitude in the extension-flexion sequence. In this sequence the duration of movement for the high ID/large movement amplitude condition increased substantially compared with the low ID/small movement amplitude condition. In addition, changing ID of the second segment influenced the time between the two segments (intersegment interval) in the extension-flexion sequence. Collectively, these data suggest that the planning of complex movements is based in part on the accuracy demands of multiple segments of the sequence.

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Introduction

Factors related to movement complexity (target size and movement amplitude) are known to affect the planning and execution of discrete movements. The relationship between speed and accuracy in performing these movements is the basis for Fitts' law (Fitts 1954; Soechting 1984; MacKenzie et al. 1987; Marteniuk et al. 1987; Weiss et al. 1996). These changes in movement kinematics are thought to reflect differences in how motor planning processes organize the neural substrate that underlies the movement.

The notion of organizing movements into some form of functional unit has been discussed extensively. Rejecting the idea of simple associative chains of reactions in which feedback from one movement stimulates the initiatiation of the next movement in a chainlike fashion, Lashley in 1951 was largely responsible for introducing the concept of a plan or motor program that guides the sequence of action. Since that time many researchers have demonstrated that, with practice, discrete responses are often organized into a sequential pattern. This integration of sequential actions also has been shown in the absence of peripheral feedback (Fentress 1973; Taub et al. 1973; Sainburg et al. 1995). Moreover, others have proposed that movements are organized into "chunks," characterized by the functional linkage created between successive movement subcomponents (Lashley 1951; Bernstein 1967; Sternberg et al. 1990; Rosenbaum 1991). Chunks are typically identified as sequential movements that share a common timing unit or reduced intersegment interval (Povel and Collard 1982; Rosenbaum 1987). Adam et al. (1995) found evidence of "chunking" in forward and backward reciprocal movements, with the feature of chunking being modified depending on the task constraints (i.e., target size).

There have been very few efforts to examine whether there are also kinematic changes in the movements that form these organizational units. One such study was performed by Marteniuk et al. (1987), who examined a movement that contained three subcomponents, wrist transport, finger grasp, and object displacement. Marteniuk et al. (1987) showed that the reaching component was influenced by the functional requirements of the displacement component. They found that when subjects had to grasp an object and place it into a small well rather than throw it into a large box, the kinematics of the reaching component were dramatically altered. Movement time and deceleration time of the reach were prolonged when the subjects were required to accurately place the object. Since the final phase of the task influenced how the initial component was executed, these data demonstrated that the way in which the object was grasped determined the kinematics of the wrist transport. This finding was interpreted as evidence that motor planning/organization processes organize all components as a functional unit based on the constraints of the complete task. These kinematic changes are a result of one movement segment influencing another, which may reveal how motor planning/organization processes specify multicomponent movements.

Several studies have shown that, when a discrete single movement to a defined target is compared with the identical movement executed in a series, this movement has a longer duration than when it is executed alone (Fischman 1984; Christina and Rose 1985; Chamberlin and Magill 1989; Sidaway 1991; Fischman and Reeve 1992). This finding has been interpreted to be the result of on-line programming in which some of the programming for the subsequent movement occurs during execution of the initial movement (Chamberlin and Magill 1989). Others have interpreted this finding to be the result of changes in movement organization that are involved in executing multiple segment movements (Fischman 1984; Christina and Rose 1985; Sidaway 1991; Fischman and Reeve 1992). However, none of these studies provided a description of the changes in movement organization caused by multiple actions. These experiments measured primarily movement time, thus insights into how the context of the movement situation influences motor planning/organization are limited.

As an extension of the preceding studies, Adam et al. (1993) measured the kinematics of a single discrete movement and a two-segment reciprocal movement in order to understand why the initial segment has a longer duration when it is executed as part of a movement series. Their data showed that the longer duration effect is only present when the impact force of the initial segment needs to be controlled. Restricting the impact force of the initial movement segment reduced the movement's peak velocity and prolonged the deceleration phase. This finding suggests that, when it is appropriate, motor planning/organization processes are influenced by the terminal accuracy constraints (force control) of both movement segments when executed in a sequence.

The effect of task difficulty on multicomponent movements is not as apparent. Several questions exist regarding the planning of these complex movements. How do motor planning/organization processes treat two segment movements that differ in difficulty? When such disparities occur, does the difficulty of one segment influence the performance of the entire movement?

The present study examines the influence of altering task demands on the kinematics of two different but related two-segment movements. One sequence is an extension-extension movement, the other is an extension-flexion movement. The index of difficulty of the second segment is changed by altering both movement amplitude and target size. Fitts' law predicts that, as the index of difficulty is modified, corresponding changes in movement kinematics in that segment will be observed. This experiment was designed to determine whether the difficulty of the second segment of a two-segment movement sequence will influence the kinematics characterizing the execution of the first segment. The experiment also addresses whether this influence generalizes across two types of sequence combinations. If this occurs, then the planning of the movement reflects task constraints that relate to the entire movement sequence.

Materials and methods

Subjects

Twenty-three subjects (10 men, 13 women; aged 19–35 years) participated in this study. They were all right-handed and with no known neuromuscular deficits. They signed consent forms prior to participation.

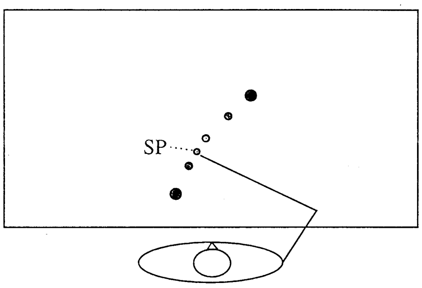
Apparatus and procedure

The experimental setting is shown in Fig. 1a. Subjects sat comfortably in a chair in front of a Calcomp 9100 horizontal digitizing table (100-Hz sampling frequency, 0.1-mm spatial accuracy). The digitizer recorded *x* and *y* position data during the movement. The digitizer was linked to a computer (PC486), which generated an auditory signal to move and stored the data.

All subjects performed eight types of two-segment arm movements in the horizontal plane. They wore a wrist brace to minimize wrist movement and held a stylus in a manner similar to that used in holding a pen. All movements were single-joint movements employing elbow flexion/extension. At the start of a trial, the subjects positioned the stylus in the starting position (1.0 cm in diameter). The subjects' task was to make two-step movements: subjects moved the stylus from the starting position to the first target and then to a second target. It was emphasized in the instructions that the goal of the task, however, was to reach the second target as quickly and precisely as possible after an auditory "go" signal.

All subjects made an extension movement away from the trunk to a common first target as a first segment (2.5 cm in movement amplitude), which shared the same target location throughout the experiment. The movement amplitude, target size, and movement direction of the second segment was varied across eight possible second segments. All target locations and indexes of difficulty (ID) are shown in Fig. 1b. The direction of the second target was either in the same directions or in the opposite direction to the movement used to execute the first segment. Thus, the subjects made extension-extension sequence movements or extension-flexion sequence. Two different distances of the second target were used; the shorter distance was 5 cm (small amplitude) and the longer distance was 10 cm (large amplitude) from the first common target.

(a) Experimental Setting



(b) Target Manipulation

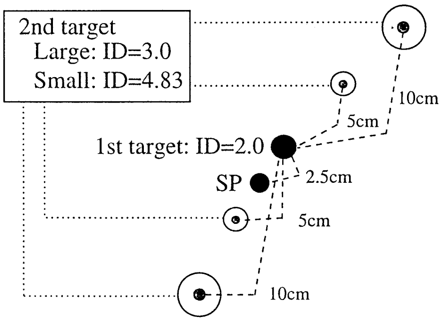


Fig. 1 The experimental setting (**a**) and target locations (**b**). In **b** note that the starting position (*SP*) and first target are always the same. The second segment was either made by continuing away from the body or by making a reversal and moving toward the trunk. The second segments were changed by modifying movement amplitude and/or target size (*ID* index of difficulty)

The size of the target was varied to attain prespecified IDs according to Fitts' law. The diameter of the first common target was 1.25 cm with an ID of 2.0. The size of the second target was adjusted to attain an ID of 4.83 and 3.0 regardless of the movement amplitude. This was accomplished by using target sizes of 0.35 cm and 1.25 cm in diameter for the small amplitude and 0.7 cm and 2.5 cm in diameter for the large amplitude. Using this arrangement, the two different IDs (4.83 and 3.0) and two different amplitudes (5 cm and 10 cm) were combined with the two movement sequences to produce eight possible conditions, which were randomized. As a control condition, a single segment movement from the staring position to the first target was performed. For the two segment movement conditions, the starting position, the first, and the selected second target were shown to the subject prior to each trial. Subjects made five practice trials before data collection began for each condition. Subsequently, the subjects performed a block of ten trials for each condition; analysis was based on these trials. For the control condition, the starting position and the first target were shown to the subject prior to each trial. Twenty trials, a block of ten trials each at the beginning and the end of the experiment, were recorded.

The movement path was recorded and displayed on a computer monitor, which allowed the examiner to determine whether the trial was executed properly. Trials were rejected if the subject either missed a target or made an obvious hesitation before entering the target. Overall, subjects made few errors, most occurred in the condition with a high ID. A total of 100 trials for each subject were collected and analyzed.

Data analysis

Position data were sampled at 100 Hz and filtered at 10 Hz. Velocity was calculated by using the first derivative of the position data. Movement onset for each segment was defined as the time at which velocity exceeded 10 mm/s. The movement offset of each segment was also calculated as the velocity at the last sampling point before it declined below 10 mm/s.

For kinematic analysis of the two-segment movement: (1) movement time, (2) time to peak velocity, (3) deceleration time, and (4) peak velocity were measured for each segment. The inter-segment interval was measured as the interval from the offset of first segment to the onset of the second segment.

For each subject a median value for the ten trials was obtained for each of the two-segment movement conditions. Similarly a median value for the 20 control condition trials was obtained for the single-segment movement. These median values were used for statistical analysis. The statistical analysis was carried out separately for each movement sequence. A 2x2 ANOVA with repeated measures was used. The independent variables were two IDs and two movement amplitudes. The probability level for statistical significance was $P \leq 0.05$. However, all calculated P-values are given in the Results section.

Results

Hand spatial trajectories and velocity profiles of the movements are shown in Fig. 2. The first and third rows are the spatial trajectories of a typical subject for movements to each of the four target locations. Trajectories show that for the first segment the subject made a forearm extension movement away from the trunk toward the first target and this movement was the same for all conditions. During the execution of the second segment in extension-extension sequence (Fig. 2a), the subject continued to extend the forearm away from the trunk to the second target. For the extension-flexion sequence (Fig. 2b), the subject made a movement reversal to execute a flexion movement to the second target. Since the subject showed basically the same spatial trajectory profiles for the high and low ID conditions, only the movements to the low ID conditions are shown.

Velocity profiles of a trial from one subject are plotted for the two ID conditions for each movement amplitude and sequence combination (Fig. 2). Notice that in the extension-extension sequence (Fig. 2a) changing ID of the second segment affects the velocity profiles of both segments. For the second segment, peak velocity decreased, and the movement duration increased for movements with the higher ID. These profiles are similar for both the small and the large amplitude movements. It is apparent from the graphs that, for the first segment, movement duration is increased for the higher ID movements. These plots suggest the existence of a context-related effect by which the difficulty of the second segment influences the performance of the first segment. Movements of the extension-flexion sequence (Fig. 2b) show similar trends in the velocity profiles of movements of the extension-extension sequence. A decreased peak velocity for the high ID movements during of the first segment is apparent in these records. The context effect of changing the ID of the second segment is also apparent.

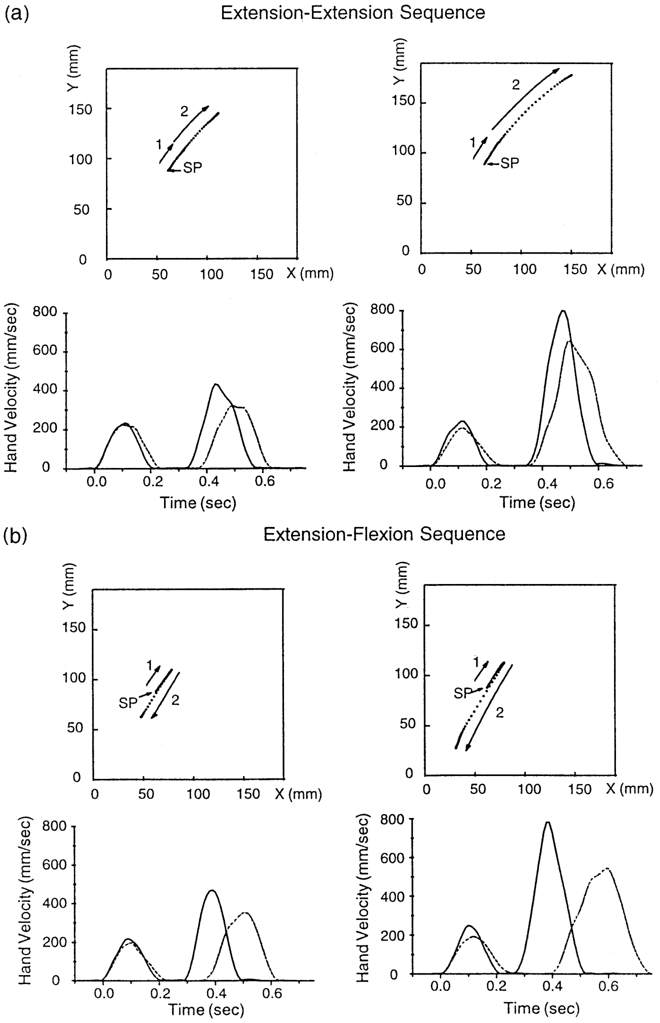


Fig. 2a, b Hand spatial trajectories and velocity profiles of two-segment movements. The small amplitude of the second segment is in the *left panel* and the large amplitude is in the *right*. Velocity profiles from one trial for each low and high ID condition are superimposed and synchronized at the movement onset. The *solid line* refers to the low ID condition and the *dashed line* refers to the high ID condition

In the remainder of the Results section the data characterizing the movements to the second segment are presented to establish that task difficulty (ID) of the second segment influenced the performance of this segment (Fitts' law; Fitts 1954). It is essential that ID effects on this segment are established before meaningful comparisons can be made on movements employed in executing the first segment. Subsequently, the "context" effect, how alternations in the ID of the second segment influences the first segment, will be presented.

Changes in the kinematics of the second segment

Extension-extension sequence

Index of difficulty. The kinematics of the second segment were affected by changing the ID of this segment as seen in Table 1 and Fig. 3. As expected from Fitts' law, movement to the small targets, which had a higher ID, exhibited longer duration. The ID main effect of movement time was significant statistically between IDs ($F_{1,22}$ = 35.05, P<0.001). When the ID was increased, the mean movement time was prolonged by 67 ms for the small amplitude and 58 ms for the large amplitude (Fig. 3a). Several kinematic parameters of the movement (Fig. 3b-d) were influenced significantly by the higher ID: lower peak velocity ($F_{1,22}$ = 52.89, P<0.001), prolonged time to peak velocity ($F_{1,22}$ = 17.53, P<0.001), and prolonged deceleration time ($F_{1,22}$ = 22.99, P<0.001). For the mean values see Table 1.

Movement amplitude. As can be seen in Table 1 and Fig. 3, the movement amplitude also affected the kinematics. The difference in the mean movement time for the two movement amplitudes was 64 ms for the low ID condition and 55 ms for the high ID condition (Fig. 3a). The mean difference between amplitudes was significant statistically for movement time ($F_{1,22}$ = 45.04, P<0.001). When the movement was decomposed into kinematic parameters (Fig. 3b–d), they were influenced significantly by the larger amplitude: higher peak velocity ($F_{1,22}$ = 185.17, P<0.001), prolonged time to peak velocity ($F_{1,22}$ = 60.20, P<0.001), and prolonged deceleration time ($F_{1,22}$ = 31.54, P<0.001). See Table 1 for exact means. No interaction effects between index of difficulty and movement amplitude on the second segment were observed.

Extension-flexion sequence

Index of difficulty. The kinematics of the second segment were affected by the ID as seen in Table 1 and Fig. 3. Similar to the extension-extension movements, the ID main effect of movement time was significant statistically between IDs ($F_{1,22}$ = 48.81, P<0.001). When the ID was increased, the mean movement time was prolonged by 68 ms for the small amplitude and 104 ms for the large amplitude (Fig. 3e). As a result, the kinematic parameters (Fig. 3f–h) changed significantly when a higher ID was used: a lower peak velocity ($F_{1,22}$ = 44.57, P<0.001), longer time to peak velocity ($F_{1,22}$ = 16.60, P<0.001), and a longer deceleration time ($F_{1,22}$ = 43.26, P<0.001). See Table 1 for mean values.

Movement amplitude. As can be seen in Fig. 3 and Table 1, the movement amplitude also affected the kinematics of the second segment. Similar to the extension-extension movements, larger amplitude movements lasted significantly longer ($F_{1,22}$ = 88.91, P<0.001). The movement time was 44 ms longer for the low ID condition and 80 ms for the high ID condition (Fig. 3e). Several kinematic parameters of the movement (Fig. 3f–h) were influenced significantly by the larger amplitude: higher peak velocity ($F_{1,22}$ = 237.57, P<0.001), prolonged time to peak velocity ($F_{1,22}$ = 44.66, P<0.001), and prolonged

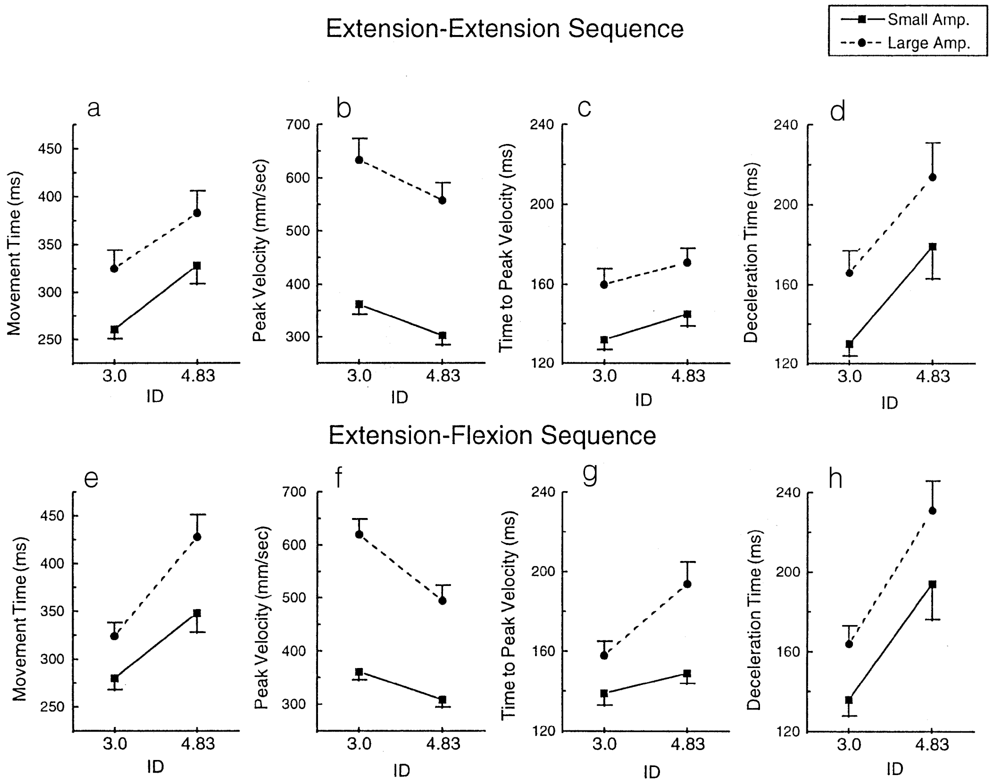


Fig. 3a–h Effects of changing index of difficulty (*ID*) on the second segment for the extension-extension sequence (*top row*) and for the extension-flexion sequence (*bottom row*). Means for all subjects are plotted in terms of movement time, peak velocity, time to peak velocity, and deceleration time. The values are plotted against the ID. The *error bars* present the SEM

Table 1 Mean and SEM for the index of difficulty and the movement amplitude conditions for the extension-extension and extension-flexion sequences

		Extension-extension sequence				Extension-flexion sequence			
Movement amplitude:		Small		Large		Small		Large	
Index of difficulty:		3.0	4.83	3.0	4.83	3.0	4.83	3.0	4.83
Reaction time (ms)	Mean	227	241	220	226	221	233	226	220
	SEM	11	13	9	11	9	12	12	10
Total movement time (ms)	Mean	595	690	655	729	566	664	589	751
	SEM	24	36	31	33	29	31	26	37
Intersegment interval (ms)	Mean	126	138	124	127	73	87	55	82
	SEM	9	10	8	10	15	15	12	15
Second segment									
Movement time (ms)	Mean	261	328	325	383	280	348	324	428
	SEM	10	19	19	23	12	20	14	23
Time to peak velocity (ms)	Mean	132	145	160	171	139	149	158	194
	SEM	5	6	8	7	6	5	7	11
Deceleration time (ms)	Mean	130	179	166	214	136	194	164	231
	SEM	6	16	11	17	8	18	9	15
Peak velocity (mm/s)	Mean	362	303	634	558	361	309	620	495
	SEM	19	18	40	33	15	14	29	29

deceleration time ($F_{1,22}$ = 18.59, $P<0.001$) for larger movements. See Table 1 for the mean values.

Index of difficulty and movement amplitude interactions. As seen in Fig. 3f and g, the effect of changing the ID differed depending on the movement amplitude. The interaction effects of ID and movement amplitude were significant statistically for peak velocity ($F_{1,22}$ = 11.66, $P<0.01$) and time to peak velocity ($F_{1,22}$ = 7.33, $P<0.05$). From the figure, it is apparent that peak velocity dropped more drastically as a function of ID in the large-amplitude movement than in the small-amplitude movement (Fig. 3f). Similarly, the time to peak velocity was prolonged substantially in the large-amplitude movement compared with the small (Fig. 3 g). Movement time (Fig. 3e) just failed significance ($F_{1,22}$ = 4.08, $P = 0.056$). No interaction was found in the deceleration time.

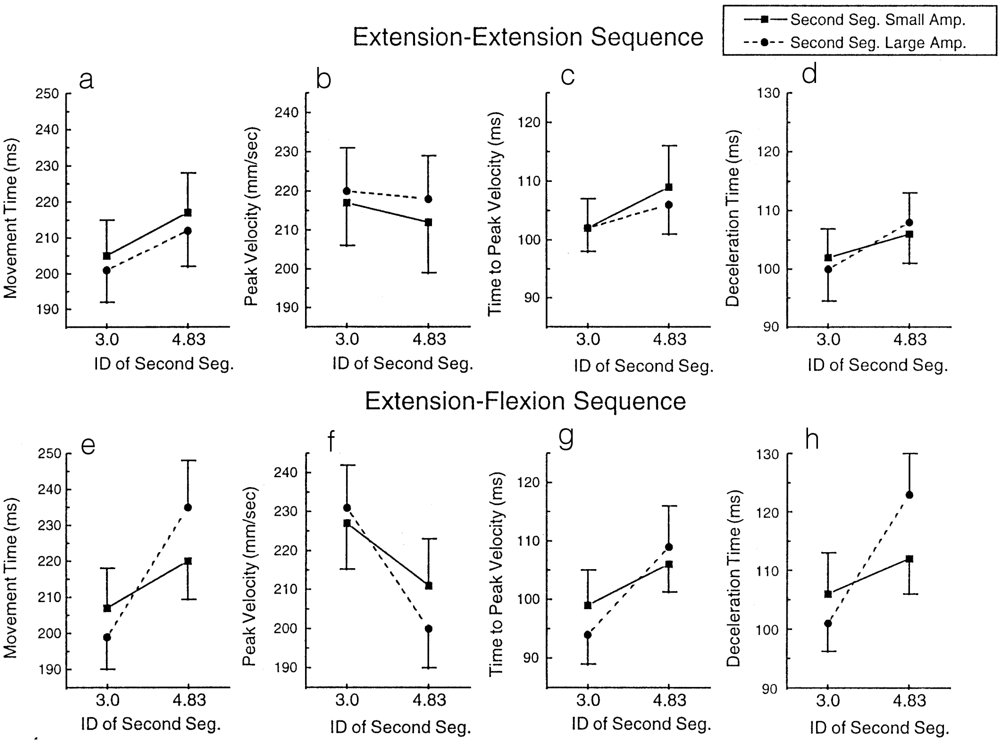


Fig. 4a–h Effects of changing index of difficulty (ID) on the first segment for the extension-extension sequence (*top row*) and for the extension-flexion sequence (*bottom row*). Means for all subjects are plotted in terms of movement time, peak velocity, time to peak velocity, and deceleration time. The values are plotted against the ID. The *error bars* present the SEM

Table 2 Mean and SEM for the index of difficulty and movement amplitude conditions for the extennsion-extension and extension-flexion sequences, for the first segment

		Extension-extension sequence				Extension-flexion sequence			
		Second segment characteristics				Second segment characteristics			
Movement amplitude:		Small		Large		Small		Large	
Index of difficulty:		3.0	4.83	3.0	4.83	3.0	4.83	3.0	4.83
First segment									
Movement time (ms)	Mean	205	217	201	212	207	220	199	235
	SEM	10	11	9	10	11	11	9	13
Time to peak velocity (ms)	Mean	102	109	102	106	99	106	94	109
	SEM	5	7	4	5	6	5	5	7
Deceleration time (ms)	Mean	102	106	100	108	106	112	101	123
	SEM	5	5	5	5	7	6	5	7
Peak velocity (mm/s)	Mean	217	212	220	218	227	211	231	200
	SEM	11	13	11	11	12	12	11	10

Changes in the kinematics of the first segment

Extension-extension sequence

Index of difficulty. Despite the fact that the first segment was constant across all conditions, the kinematics of this segment were also affected significantly by changing the ID of the second segment. As can be seen in Fig. 4a, movement time of the first segment was significantly longer when the second segment had a higher ID ($F_{1,22}$ = 16.15, P<0.001). It was prolonged by 12 ms for the small amplitude and 11 ms for the large amplitude. In addition, the time to peak velocity ($F_{1,22}$ = 9.52, P<0.01; Fig. 4c) and deceleration time ($F_{1,22}$ = 9.67, P<0.01; Fig. 4d) were increased significantly for the higher ID. Peak velocity did not vary significantly between the two IDs (Fig. 4b). See Table 2 for the mean values.

Movement amplitude. As can be seen in Fig. 4a–d, most of the differences between the small and large amplitudes are rather small. Changes in movement amplitude from small to large did not affect any kinematic parameter of the first segment. The means of the various parameters are available in Table 2.

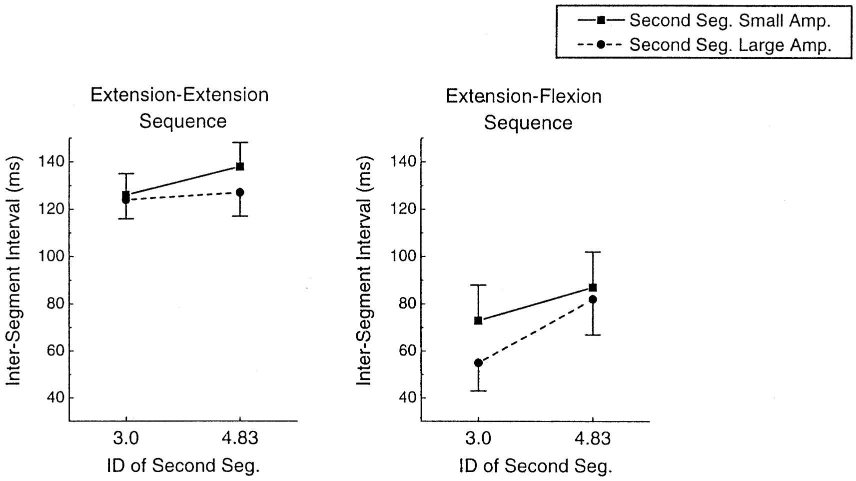


Fig. 5 Effect of changing index of difficulty of the second segment on intersegment intervals (the time between the two segments) for extension-extension and extension-flexion sequence. Mean values are plotted against the ID. The *error bars* present the SEM. *Squares* second segment, small amplitude; *circles* second segment, large amplitude

Extension-flexion sequence

Index of difficulty. Kinematics of the first segment were clearly affected by varying the ID of the second segment. As can be seen in Fig. 4e, when compared with the low ID, movements with high ID took significantly longer ($F_{1,22}$ = 26.94, P<0.001). It was prolonged by 13 ms for the small amplitude and 36 ms for the large amplitude. As seen in Fig. 4f, the high ID condition produced a lower peak velocity ($F_{1,22}$ = 26.35, P<0.001). A similar pattern can be seen in Fig. 4 g and h; both time to peak velocity ($F_{1,22}$ = 20.71, P<0.001), and deceleration time ($F_{1,22}$ = 12.71, P<0.001) increased significantly for the higher ID. See Table 2 for the mean values.

Movement amplitude. Variation in movement amplitude did not produce any main effect on the first movement. These mean values are reported in Table 2.

Index of difficulty and movement amplitude interactions. As is apparent in Fig. 4e, f, and h, the effect on the first segment of changing ID of the second segment was altered dependent upon the amplitude of the second segment. Longer movement duration, lower peak velocity, and longer deceleration time for the higher ID condition were more pronounced for large amplitude than small amplitude ($F_{1,22}$ = 6.59, P<0.05; $F_{1,22}$ = 5.04, P<0.05; and $F_{1,22}$ = 6.02, P<0.05, respectively). No other significant interactions were observed.

Intersegment interval

The time period between the two segments during which the forearm velocity dropped below 10 mm/s was defined as the intersegment interval. Figure 5 reveals that the inter-segment interval is much longer in the extension-extension sequence than extension-flexion sequence. This difference was significant ($F_{1,22}$ = 25.34, P<0.001). Also these data suggest that the intersegment intervals are larger for the higher ID. However, changing ID of the second segment significantly affected the intersegment interval only in the extension-flexion sequence. The duration of the interval was longer significantly for second movements with the higher ID ($F_{1,22}$ = 7.08, P<0.05). See Table 1 for the mean values.

Discussion

As anticipated, changing the ID of the second segment influenced the performance of that segment's kinematics for both extension-extension and extension-flexion sequences. By increasing ID, it was observed that movement time was lengthened, peak velocity was reduced, and the deceleration phase was prolonged. These findings are consistent with numerous previous studies that utilized Fitts' law to vary movement difficulty (Fitts 1954; Soechting 1984; MacKenzie et al. 1987; Marteniuk et al. 1987; Goggin and Meeuwsen 1992; Weiss et al. 1996).

The most informative part of these current data is that changing the ID of the second segment also influenced the movement kinematics of the first segment. For the extension-extension sequence, the larger ID of the second segment increased the movement time of the first segment, which was reflected by a prolonged time to peak velocity and the deceleration time (Fig. 4a, c, d). These changes paralleled the changes observed in the second segment. The extension-flexion movement sequence also revealed a similar result. Increasing the ID of the second segment not only prolonged movement time of the first (Fig. 4e) but also lowered its peak velocity (Fig. 4f). This effect of context dependency on the performance of the first segment suggests that the central nervous system (CNS) considers the features of both segments in its planning and organization of the movement sequence. These processes appear to scale velocity of the first segment in relation to the difficulty of the second segment. This type of effect has been labeled a "context effect" by Rosenbaum (1991) and is assumed to reflect program control. Based on the view of context effect, skill acquisition is thought to take the form of a concatenation of movements. Gradually with practice,

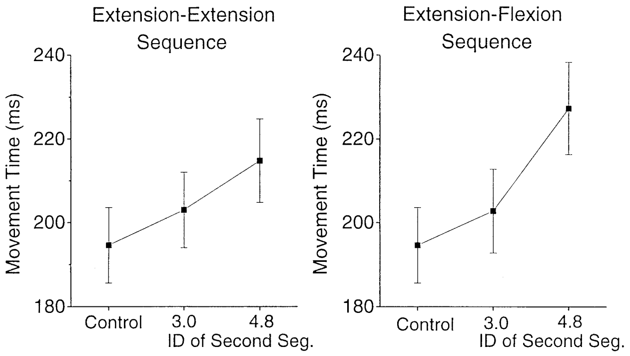


Fig. 6 Movement time of a single-semgent movement (control) and the first segments of the two-segment movements in which the second-segment ID was 3.0 or 4.83. The *error bars* present the SEM

concatenation is replaced by program control, with the program for controlling an entire sequence represented at a higher level than to the programs for each segment (Stelmach and Diggles 1982).

In accepting the view that movements are programmed together, one must be certain that the initial movement in the sequence was not totally ignored[1]. We feel that for the task used in this experiment this was not the case, because the terminal accuracy constraint on the first segment was extensive. The initial segment movements had to end in a 1.25-cm target location that required precise terminal control (2.0 ID). In addition velocity curves for the initial segment movement exhibited single-peak, bell-shaped profiles that began and ended with zero velocities (see Fig. 2). Both of these factors suggest that the initial movement was fully prepared and executed. Nevertheless, to further exclude this possibility, we also compared the first segment when executed alone and when it was part of the two-segment movement. This control condition is described in the Materials and methods section. The comparison revealed that, for the extension-extension and extension-flexion sequences, the first segment of the two-segment movement had a longer duration than when it was executed alone. These data are shown in Fig. 6. In the extension-extension sequence, mean movement time of the first segment was 194 ms for the single-segment control condition, while for the two-segment conditions it was 203 ms and 214 ms for 3.0 ID condition and 4.83 ID condition, respectively. Similarly in the extension-flexion sequence, the mean value was 194 ms for the single-segment control condition, while for the two-segment conditions it was 202 ms and 227 ms for 3.0 ID and 4.83 ID conditions, respectively. These data clearly show that, when executing the two-segment movements (extension-extension and extension-flexion), the first segment has a slightly longer duration than when it is executed in isolation. These data provide additional support that the initial segment was fully prepared and executed in the sequence. Our findings are not alone in this regard. Temporal prolongation of an initial segment, when executed in a movement series, has been reported by others as mentioned previously (Fischman 1984; Christina and Rose 1985; Chamberlin and Magill 1989; Sidaway 1991; Adam et al. 1993).

In three related papers, movement organization of the first segment in a two-segment movement has been shown to be influenced by the target size of the second segment. Movement time of the first segment was longer when the target size of the second was reduced (Adam et al. 1995; Sidaway et al. 1995; Short et al. 1996), this finding is in agreement with our results. Sidaway et al. (1995) demonstrated that spatial dispersion of movement endpoints around the first target was reduced when the target size of the second movement of the two-segment movement was decreased, thereby increasing the accuracy demand. Using a similar target size manipulation, Short et al. (1996) reported that the movement pathway of the first segment contained less horizontal deviation and higher peak vertical displacement than when the movements were made to larger targets in the second segment. These latter two experiments suggest that the accuracy constraint of the second movement influences how the first segment is prepared and executed. These results are also similar to those reported in this experiment. While these latter two experiments showed the influence of the second segment on the movement pathway of the first segment, our study shows that kinematic features such as peak velocity, time to peak velocity, and deceleration time are also influenced by the accuracy constraint of the second segment. Furthermore, our data demonstrate that the context dependencies observed affect both extension-extension and extension-flexion movements similarly.

While some data have suggested that motor planning processes may group multiple segment movements into a functional unit, the empirical demonstration of such grouping has not been dramatic. For example, Adam et al. (1995) reported that repetitive movements are organized in chunks. However, only part of their data supported such an interpretation, since only the large target of the first segment (6 cm in diameter) in the two-segment sequence induced a chunk phenomenon. Weiss et al. (1997) also reported some evidence of context dependency between segments in a movement sequence. However, the observed correlations between the duration of the segments, regardless of whether calculated on a group or individual-subject bases, did not reflect consistent patterns of temporal dependence. Similarly, Marteniuk et al. (1987), using a prehension task, showed that the trajectory of the reach is altered depending on whether the subjects placed or threw a grasped object. These data were interpreted as supporting the notion that planning processes are based on the functional demand of entire task, when organizing multiple movement segments. This information is then used to specify how the trajectory of the reach is executed. While the Marteniuk et al. (1987) data show context dependency, they may not reflect how the CNS organizes the prehension task as much as how momentum and inertia influence the reach when throwing an object or placing it.

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[1] We are indebted to an anonymous reviewer for this suggestion

Neurophysiological studies also have shown evidence for context-dependent effects in movement tasks. Experiments that examined neural correlates of sequential movements demonstrated that the discharge of neurons in several locations can be correlated not only with a movement segment but also with the context in which the movement is executed (Strick et al. 1995; Tanji et al. 1995). For example, some neurons in the basal ganglia show different neural activation patterns depending on whether a monkey performed a precued, three-sequence button-press task or three successive discrete button presses of the same sequence (Strick et al. 1995). The major difference between the two conditions was whether or not the monkey knew the entire sequence before moving. Similar context-dependent observations were reported for neurons in the supplementary motor area using combinations of turn-pull-push movements over the elbow joint (Tanji et al. 1995).

While direct comparisons were not made between sequence combinations based on kinematic parameters, the observed context effects were larger in the extension-flexion sequence than in the extension-extension sequence (Fig. 4). For the extension-flexion sequence, prolonged movement duration and reduced velocity were observed, whereas only movement duration was prolonged in the extension-extension sequence. Also, changing ID significantly affected the intersegment interval only in the extension-flexion sequence (Fig. 5). These relative differences in the context effect related to the two sequences might reflect differences in their planning and organization. Larger context dependency observed in the extension-flexion movement suggests that the execution of this sequence was temporally better integrated than that of the extension-extension sequence, thereby creating a larger context dependency. Support for this interpretation comes from the movement duration and peak velocity data seen in Fig. 4, which shows an increased velocity of the first segment in this sequence. It is also feasible that the muscle activation pattern in the first sequences is more conducive to performing a flexion than an extension in the second segment. Enoka (1994) reported that the first segment of a reciprocal movement consisted of a biphasic agonist-antagonist electromyographic (EMG) pattern. For the extension-flexion sequence, the activated antagonist during the first segment would be expected both to decelerate the initial movement and enhance the initiation of the subsequent segment. Having the deceleration and reinitiation of the next segment dependent on the same muscle could have produced a shorter intersegment interval than occurs for the extension-extension sequence, which requires the reactivation of the original agonist to initiate the movement in the second segment (Fig. 5). The influence of changing ID on the intersegment interval was found only in the extension-flexion sequence (Fig. 5). For the 3.00 ID the mean intersegment interval was 64 ms (the mean of both amplitudes), and for the 4.83 ID the mean interval was 84.5 ms. The short interval between segments in this sequence reduces the possibility for any on-line corrections, thus requiring more complete programming of all the movement features prior to execution. This may have resulted in the sensitivity of the intersegment interval to changes in ID.

An interaction between the ID and movement amplitude was observed in the extension-flexion sequence. In this sequence the high ID/large-amplitude condition produced the longest movement duration and the slowest peak velocity (Fig. 3e, f) in the second segment. Interestingly, similar slowing of the movements in this condition also was observed in the first segment (Fig. 4e, f). This demonstrates the strength of the context dependency observed and suggests that the difficulty of both segments is considered when the sequence is prepared. One reason for the movement slowing in this high ID/large-amplitude condition may be the spatial location of the second target in relation to the posture of the subjects. The location of the target was contralateral to the side of the moving arm. Fisk and Goodale (1985) reported that aiming movements in the working space contralateral to the hand used were slower and less accurate. In addition, the accuracy impairment was much pronounced for more eccentric target. Thus the general slowness and inaccuracy in movements in this working space might have contributed to the observed pattern, and movement slowness was enhanced by the higher accuracy demand toward the small target, especially in the large movement amplitude.

In contrast to ID findings, movement amplitude (extent of movement), when considered as a separate factor, did not influence the kinematics of the first segment (Fig. 4). Higher peak velocity was observed for the large-amplitude movements of the second segment, showing that movement velocity was scaled according to movement amplitude (Freund and Büdingen 1978; Berardelli et al. 1984; Brown and Cooke 1984;). This implies that changes in the extent of the movement may not affect dramatically the establishment of the motor program or that longer movements do not need to be fully programmed (Klapp 1975). If the latter occurs, on-line adjustments would be required to guide the hand to the target. Earlier studies have shown that, when a movement amplitude was programmed at the time of the imperative go signal, reaction time was prolonged for only a few milliseconds compared with the condition in which the subject knew the movement amplitude before the go signal (Stelmach et al. 1987). In comparison with other movement features such as selection of arm and movement direction, the effect of movement amplitude on reaction time was minimal (Rosenbaum 1980; Stelmach et al. 1987). Similarly, if a movement's amplitude must be restructured at the time of initiation, the time cost to restructure the amplitude is minimal compared with that required for changes in direction or for selecting the arm to be utilized (Stelmach et al. 1988). Thus, the impact of programming amplitude on the movement's kinematics appears to be substantially less than that of planning features of the movement constrained by target size. Such a dissociation between target size and movement amplitude in the motor planning of a multisegment movement has not been previously reported.

In summary, the difficulty (ID) of the second segment of a two-segment movement sequence influenced the kinematics characterizing the execution of the first segment. The movement duration of the first segment was prolonged and peak velocity was lowered when ID of the second segment was increased by reducing the target size. This context-dependent influence generalized across both types of sequence combinations as well as across different movement amplitudes. Collectively, the present data clearly establish that the accuracy constraints related to executing a segment within a movement sequence affect the planning and organization of the entire sequence.

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References

Adam JJ, Bruggen DPW van der, Bekkering H (1993) The control of discrete and reciprocal target-aiming responses: evidence for the exploitation of mechanics. Hum Mov Sci 12:353–364

Adam JJ, Paas FGWC, Eyssen ICJM, Slingerland H, Bekkering H, Drost M (1995) The control of two-element, reciprocal aiming movements: evidence for chunking. Hum Mov Sci 14:1–11

Berardelli A, Rothwell JC, Day BL, Kachi T, Marsden CD (1984) Duration of the first agonist EMG burst in ballistic arm movements. Brain Res 304:183–187

Bernstein N (1967) The coordination and regulation of movements. Pergamon Press, London

Brown SH, Cooke JD (1984) Initial agonist burst duration depends on movement amplitude. Exp Brain Res 55:523–527

Chamberlin CJ, Magill RA (1989) Preparation and control of rapid, multisegmented responses in simple and choice environments. Res Q Exerc Sport 60:256–267

Christina RW, Rose DJ (1985) Premotor and motor reaction time as a function of response complexity. Res Q Exerc Sport 56:306–315

Enoka RM (1994) Neuromechanical basis of kinesiology. Human Kinetics, Champaign, IL

Fisk JD, Goodale MA (1985) The organization of eye and limb movements during unrestricted reaching to targets in contralateral and ipsilateral visual space. Exp Brain Res 60:159–178

Fentress JC (1973) Development of grooming in mice with amputated forelimbs. Science 179:704–705

Fischman MG (1984) Programming time as a function of number of movement parts and changes in movement direction. J Mot Behav 16:405–423

Fischman MG, Reeve TG (1992) Slower movement times may not necessarily imply on-line programming. J Hum Mov Stud 22:131–144

Fitts PM (1954) The information capacity of the human motor system in controlling the amplitude of movement. J Exp Psychol 47:381–391

Freund HJ, Büdingen HJ (1978) The relationship between speed and amplitude of the fastest voluntary contractions of human arm muscles. Exp Brain Res 31:1–12

Goggin NL, Meeuwsen HJ (1992) Age-related differences in the control of spatial aiming movements. Res Q Exerc Sport 63:366–372

Klapp ST (1975) Feedback versus motor programming in the control of aimed movements. J Exp Psychol Hum Percept Perform 104:147–153

Lashley KS (1951) The problem of serial order in behavior. In: Jeffress LA (ed) Cerebral mechanisms in behavior. Wiley, New York, pp 112-136

MacKenzie CL, Marteniuk RG, Dugas C, Liske D, Eickmeier B (1987) Three-dimensional movement trajectories in Fitts' task: implications for control. Q J Exp Psychol [A] 39:629–647

Marteniuk RG, MacKenzie CL, Jeannerod M, Athenes S, Dugas C (1987) Constraints on human arm movement trajectories. Can J Psychol 41:365–378

Povel DJ, Collard R (1982) Structural factors in patterned finger tapping. Acta Psychol 52:107–123

Rosenbaum DA (1980) Human movement initiation: specification of arm, direction, and extent. J Exp Psychol Gen 109:444–474

Rosenbaum DA (1987) Successive approximations to a model of human motor programming. In: Bower G (ed) The psychology of learning and motivation. Academic Press, New York, pp 153–182

Rosenbaum DA (1991) Human motor control. Academic Press, San Diego, CA

Sainburg RL, Ghilardi MF, Poizner H, Ghez C (1995) Control of limb dynamics in normal subjects and patients without proprioception. J Neurophysiol 73:820–835

Short MW, Fischman MG, Wang YT (1996) Cinematographical analysis of movement pathway constraints in rapid target-striking tasks. J Mot Behav 28:157–163

Sidaway B (1991) Motor programming as a function of constraints on movement initiation. J Mot Behav 23:120–130

Sidaway B, Sekiya H, Fairweather M (1995) Movement variability as a function of accuracy demand in programmed serial aiming responses. J Mot Behav 27:67–76

Soechting JF (1984) Effect of target size on spatial and temporal characteristics of a pointing movement in man. Exp Brain Res 54:121–132

Stelmach GE, Diggles VA (1982) Control theories in motor behavior. Acta Psychol (Amst) 50:83–105

Stelmach GE, Goggin NL, Gracia-Colera A (1987) Movement specification time with age. Exp Aging Res 13:39–46

Stelmach GE, Goggin NL, Amrhein PC (1988) Aging and the restructuring of precued movements. Psychol Aging 3: 151–157

Sternberg S, Knoll RL, Turock DL (1990) Hierarchical control in the execution of action sequences: test of two invariance properties. In: Jeannerod M (ed) Attention and performance XIII. Erlbaum, Hillsdale, NJ, pp 3–55

Strick PL, Dum RP, Mushiake H (1995) Basal ganglia "loops" with the cerebral cortex. In: Kimura M, Graybiel AM (eds) Functions of the cortico-basal ganglia loop. Springer, Tokyo, pp 106–124

Tanji J, Shima K, Matsuzaka Y, Halsband U (1995) Neuronal activity in the supplementary, presupplementary, and premotor cortex of monkey. In: Kimura M, Graybiel AM (eds) Functions of the cortico-basal ganglia loop. Springer, Tokyo, pp 154–165

Taub E, Perella P, Barro G (1973) Behavioral development after forelimb deafferentation on day of birth in monkeys with and without blinding. Science 181:959–960

Weiss P, Stelmach GE, Adler CH, Waterman C (1996) Parkinsonian arm movements as altered by task difficulty. Parkinsonism & Related Disorders 2:215–223

Weiss P, Stelmach GE, Hefter H (1997) Programming of a movement sequence in Parkinson's disease. Brain 120:91–102