

Force and Timing Components of the Motor Program

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ABSTRACT. Three experiments were undertaken to assess the effects of variations of force and time on both simple and choice reaction time. The first two experiments demonstrated that although latency did not vary as a function of force, timing variations, such as requiring that a response be maintained, led to consistent changes in reaction time. These results led to the development of a model of motor programming in which force and timing are dissociated as separate components. However, the data also indicated that the force component may be further analyzed into two subcomponents—force activation and force deactivation. The model predicts that the latter subcomponent may be programmed on-line provided that sufficient time elapses between the implementation of the two subcomponents. A different pair of movements was used in Experiment 3 to further demonstrate that force activation and deactivation may be preprogrammed into a single component. These results support the aspect of the proposed model that makes a distinction between operations required for program construction from those necessary for program implementation.

A BASIC ASSUMPTION underlying much research on movement control is the notion that an entire action may be centrally represented. This assumption was provided with a conceptual structure by the idea of a motor program (Keele, 1968; 1981; Schmidt, 1983). Researchers hypothesize that the program embodies both the goal of the movement and the different components that are required to attain that goal. Although the end-goal of movement has not been difficult to manipulate experimentally, identifying the different components of the motor program has proved to be much more elusive. It is obvious at the most superficial level that movement (both isometric and isotonic) entails a change in the state of the target muscles for a variable period of time. However, there are a number of different ways in which these changes can be effected; thus, it remains unclear how a central control system governs movement (see Stein, 1982, for a review of this problem).

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In the endeavor to identify the components of the motor program, many researchers have used a paradigm in which they infer movement complexity from differences found in response latency (e.g., Klapp, Wyatt, & Lingo, 1974; Rosenbaum, 1980). This paradigm has its roots in Henry and Rogers' (1960) memory drum theory. The theory proposes that more complex movements entail larger programs and, thus, more preparation time for the person to access the information required for the coordination of the neural signals needed to trigger the movement.

One finds considerably less unanimity in the literature when trying to identify what is meant by "complexity." Rosenbaum (1980) and Rosenbaum, Inhoff, & Gordon (1984) have shown that latencies increase as a function of hand selection, direction of movement, and, to a lesser degree, extent of movement. Because combinations of these factors have to be specified during the preparation period, latencies are further slowed. Thus, these researchers have approached the question of complexity by varying the amount of uncertainty. However, increasing complexity has frequently been confounded with an increase in S-R incompatibility (Goodman & Kelso, 1980) or S-R alternatives (Zelaznik, Shapiro, & Carter, 1982). Larish and Frekany (1985) have recently shown that when these potential confounds are avoided, latency profiles may be reflective of the structure of the motor program. Other researchers (Klapp, Anderson, & Berrian, 1973; Sternberg, Monsell, Knoll, & Wright, 1978) have demonstrated that in the speech domain, the number of syllables can serve as a measure of complexity. Although studies such as these are useful in showing that reaction times may increase because of the need to specify more components of a movement, they still provide only a general description of the constituents of a motor program.

A more detailed method of examining the complexity effect is encompassed in experiments in which the basic movement remains unchanged, but the parameterization of single components is varied. For instance, Baba and Marteniuk (1983) used a modified simple reaction time paradigm (go vs. no-go) to test whether varying force or varying duration led to increases in response latency. They found that for simple movements involving flexion of the elbow, RT did not increase as a function of force when duration was held constant. However, RT did increase significantly when movement duration was increased with force held constant. Klapp et al. (1974) found similar results in choice reaction time experiments. Both researchers (Baba & Marteniuk, 1983; Klapp & Erwin, 1976) speculated that the increase in latency as a function of increased movement duration may be related to the generation of more complex timing circuits. However, other studies in which force and time were not independently controlled or varied have provided less clear results. For instance, Lagasse and Hays (1973) and Glencross (1972) found that RT did not differ when subjects had to make either long or short movements. Although movement time was greater for the long movements, neither experimenter obtained any measurements of force. Thus, it is

not possible to determine the variables that their subjects manipulated to produce the different movements.

The variables that have been investigated in these studies seem especially pertinent when considering broader questions of motor control. Specifically, a number of researchers have hypothesized that force and timing may be independently controlled. For instance, both Freund and Büdingen (1978) with humans, and Ghez (1979), with cats, have found that in making rapid movements of varying force, the duration of the initial EMG burst appears to be invariant. They point out that such an organization of the system, in which certain timing aspects are invariant, greatly reduces control problems in that the subject only needs to select the appropriate force to comply with the demands of the task. Kelso, Southard, and Goodman (1979) have also presented an argument for temporal invariance to account for the coordinated velocity and acceleration profiles of two-handed movements. Of course, this research has been directed at the movement kinematics and, thus, is a few levels removed from the central control system. However, recordings from either single motor units (Tanji & Kato, 1973) or cortical cells (Smith, Hepp-Reymond, & Wyss, 1975) have also provided evidence for separate control of force and timing. Both studies have shown that although most neural units appear to fire in a direct relationship with the force required, there are some units whose firing frequency is not correlated with force, but remain constant throughout the duration of the movement. These units may be coding timing information.

The experiments reported here constitute an attempt to further clarify the effects of variations in force and time on response latencies. In Experiment 1, subjects were required to vary force while keeping response duration fairly constant, whereas, in Experiment 2, force was held constant and duration was manipulated.¹ All movements were performed isometrically by pressing against a strain gauge. This allowed for greater experimental control since neither force nor time was confounded with extent. The combined results of these two experiments led to the development of a model that specifies some of the components and subcomponents of simple movements. Experiment 3 tested a prediction of this model.

All three experiments involved both choice and simple reaction time sessions. While Klapp et al. (1974) employed a similar approach, their motivation was to demonstrate the merits of one approach over the other as a means for assessing motor programming. This has led to a long and sometimes tempestuous debate in the literature (e.g., Henry, 1980; Marteniuk & MacKenzie, 1981; Klapp, 1981). As the present experiments show, this may be an empty argument and the (unfortunate) consequence of strict adherence to the metaphor of computer programming. In the computer domain, the term "programming" is reserved for the process of constructing the program. However, in the psychological literature, "programming" has generally been used to refer to all of the events preceding response initiation. As many authors have noted, the initiation process may include distinct phases: One phase must be concerned with program construction, but an additional phase may be

necessary for implementing the program, that is, reading the program out of a holding buffer (Sternberg et al., 1978; Rosenbaum et al., 1984). Since the motor control theorist is concerned with the entire process governing movement, methodologies that allow the researcher to identify the specific processes of each phase should be viewed as an experimental aid and not as an obstacle. Choice and simple RT conditions were employed as complements in the following experiments, because both may illuminate different aspects of the response preparation period.

Experiment 1

Experiment 1 was designed to test whether varying the amount of force required to perform an isometric movement influenced choice or simple reaction time. More specifically, does programming a desired force require a constant amount of time, or is latency a function of force?

Since movements of greater force entail both the recruitment of more motor units and increases in the firing frequency of these units (e.g., Desmedt, 1983), one possibility is that movements of greater force will take longer to prepare. The notion here is that the recruitment of a greater quantity of motor units involves a more complex program due to the stronger central signal. On the other hand, Chez and Vicario (1978) have obtained the opposite latency profile in a choice reaction time paradigm with cats. They found that RT decreased with increases in force, although the asymptote was approached by their mid-range force levels.

More analogous to the present experiment is the work of Klemmer (1957). In this simple RT experiment, subjects were asked to increase their force output on a strain gauge by a varying amount. Klemmer found no differences in RT as a function of target force level. In fact, after 3600 trials on each force level, the mean RT for the small force condition was 168 ms and 169 ms for the large force condition. The short RT's indicate that subjects must have programmed the response in advance of the reaction signal. Since the simple RT phase of the present experiment is a near-replication of Klemmer's study, it is expected that the same results will be obtained. Whether the same results should be expected in the choice RT sessions is less clear. Assembling the motor program may show differences that do not appear when the measure is taken of the time needed to execute the program.

Method

Apparatus

A response key was mounted on top of a Grass strain gauge (Model FT10D). The strain gauge sent a pressure-dependent electrical signal to an amplifier, which then relayed the signal on to an analogue-to-digital (A to D) converter located in an Apple II microcomputer.

All displays were controlled by the computer, and all response measures were collected and recorded by the computer. A minimum displacement criterion to indicate movement onset was set at 1.1 Newtons

(N). Due to gravitational force, the typical person's index finger displaces 0.6 N of force simply by resting on the key. Thus, the latency was recorded after the subject had generated a force of 0.5 N. Measurements were also obtained for peak force, the time at which peak force was reached, and the duration of the press (recorded at the time the pressure recrossed the criterion point).

Subjects

Ten young adults were randomly selected from the Cognitive Laboratory Subject Pool at the University of Oregon. All were right handed with normal or corrected-to-normal vision and hearing. The subjects were paid \$6 for their efforts.

Procedure

The subjects sat in front of the display screen in a quiet, dimly lit room. They placed their right index finger on the response key. Because the subjects were required to place their thumb and other fingers on the response board, and their elbow on a table of the same height, their isometric movements were restricted to contractions of the muscles controlling the index finger.²

Three different force levels were used in this experiment. Each force level was paired with a digit, which served as the stimulus for that force level. A low target force, 4.5 N, was paired with the digit 0, a moderate target force, 7.5 N was paired with the digit 1, and a high target force, 10.5 N, was indicated by the digit 2. Since the A to D converter recorded force on an arbitrary scale from 0 (no force) to 189 (maximum force), the corresponding arbitrary values for each target force were used in both explaining the experiment to the subjects and for feedback purposes. The values 60, 100, and 140 corresponded to the 4.5 N, 7.5 N, and 10.5 N target force levels, respectively. The subject was considered to have correctly attained the target force if his or her response was within 20 arbitrary units of the target force. Thus, the acceptable range for the three conditions was: Stimulus 0: 40-80; Stimulus 1: 80-120; Stimulus 2: 120-160. If the force generated by the subject in experimental trials was either below or above the tolerance criterion, the trial was counted as an error and the message "Out of Force Range" was displayed during the feedback interval. The option of using a proportional method to determine the tolerance ranges was not used since previous research (Sheridan, 1981; Klapp & Greim, 1981) has shown that RT does not change when amplitude is held constant, but the tolerance level is varied.

In addition, two timing criteria were employed to determine the status of a trial. A trial was counted as an error if either the RT was greater than 600 ms, in which case the message "Slow Start" appeared, or if the response duration was longer than 400 ms, in which case the feedback message read "Holding Key Press Too Long." The short latency criterion of 600 ms was chosen to emphasize speed, whereas the 400 ms

duration value was adopted to ensure that all of the responses were performed rapidly.

Preliminary testing indicated that, due to the sensitivity of the strain gauge and the various criteria, the task was extremely difficult. However, since the primary interest was on the reaction times, the subjects were informed that they should focus on starting their responses quickly and should anticipate making many errors.

Simple RT condition. The sequence of events for simple RT sessions is depicted in the top half of Figure 1. A trial began when one of the stimulus numbers (0, 1, or 2) appeared on the center of the display screen. The number indicated which response the subject was to prepare. Two seconds after the target was presented, a warning tone was generated by the computer. A second tone served as the reaction signal and followed the first tone by a randomly selected interval of either 750, 1000, or 1250 ms. The subjects were instructed to respond as quickly as possible to the second tone. For one quarter of the trials, no second tone was generated; these trials were included to ensure that the subjects were responding to, rather than anticipating, the reaction signal. Therefore, in addition to the three error messages cited above, a fourth error message was "False Start" for cases in which a person responded on a catch trial. After the subject had responded (or not responded on a catch trial), the stimulus was replaced by feedback. If all criteria were met, this feedback included the maximum force attained in arbitrary units, the response duration in ms, and the message "Trial is Good." If an error was made, the appropriate error message was displayed with the force and duration values. The feedback remained on for 2000 ms, after which a new stimulus appeared to initiate the next trial.

Choice RT condition. The sequence of events for the choice RT sessions are shown in the bottom half of Figure 1. These trials were initiated by an auditory warning tone. After a randomly selected interval of either 750, 1000, or 1250 ms, a number from the set (0, 1, 2, or 4) appeared on the center of the screen. This stimulus indicated the appropriate response and also served as the reaction signal. The digit 4 was presented on one quarter of the trials and was included to create catch trials. As in the simple RT condition, any responses on catch trials were counted as errors and were followed by the message "False Start" in the feedback period. Following the subject's response, feedback was presented in the same manner as described above. The feedback stayed on for 2000 ms. The feedback was then erased and the next trial began after a 2000 ms rest period.

Each subject participated in one practice bout for each condition (simple and choice RT) and two test sessions for each condition. The practice sessions consisted of 40 trials—10 trials at each force level and 10 catch trials. Each test session was composed of 60 trials—15 trials at each force level and 15 catch trials. The order of trials within a session was randomly determined by the computer. All trials in which errors occurred were repeated by being placed back into the set of remaining trials. Thus, at the end of the experiment, each subject had generated 30

Figure 1. Sequence of events for the simple and choice RT conditions in all three experiments.

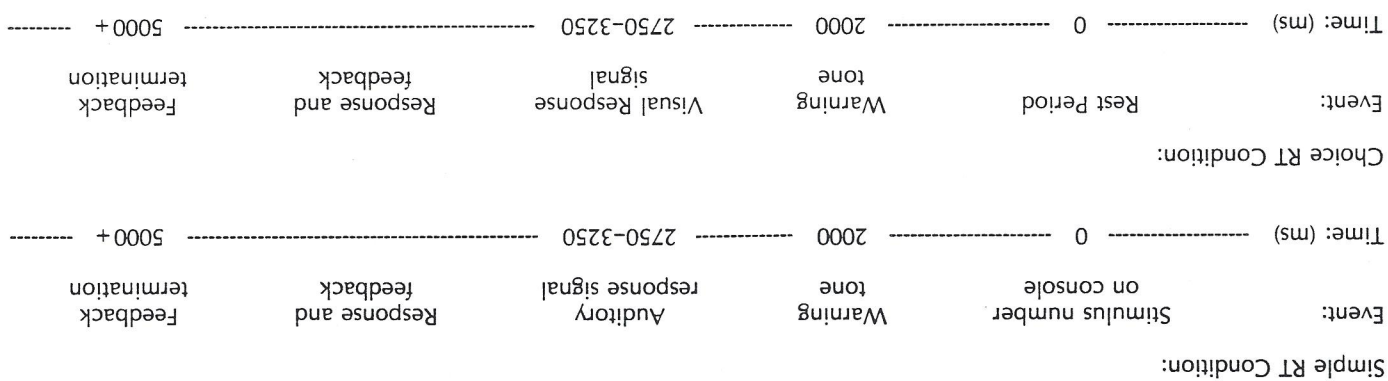


Table 1
Means and Standard Deviations for Experiment 1

Force range	Stimulus	Latency	Force	Response duration	Time to peak force	Slow starts	Force errors
				Simple RT condition			
40 - 80	0	283 (58)	62 (10)	174 (22)	72 (18)	.00	.07
80 - 120	1	282 (62)	100 (11)	206 (23)	88 (18)	.00	.10
120 - 160	2	291 (63)	138 (11)	242 (31)	109 (23)	.00	.14
Means		285	—	207	90		
				Choice RT condition			
40 - 80	0	476 (75)	60 (11)	170 (24)	67 (17)	.04	.06
80 - 120	1	458 (65)	100 (11)	218 (35)	91 (25)	.03	.08
120 - 160	2	454 (65)	138 (11)	254 (39)	114 (28)	.04	.12
Means		463	—	214	91		

Note. Force measures are in terms of the arbitrary units of the A to D converter, and the timing measures are in ms. Error rates are in terms of proportion of total trials for each RT condition.

error-free data points for analysis at each of the three force levels in both the simple and choice RT conditions.

The order of conditions for half of the subjects was: practice simple RT, test simple RT, practice choice RT, test choice RT, test simple RT, and test choice RT. The other half of the subjects started with practice choice RT and a test choice RT session, followed by practice simple RT, test simple RT, test choice RT, and test simple RT.

A complete experimental session lasted approximately 90 mins.

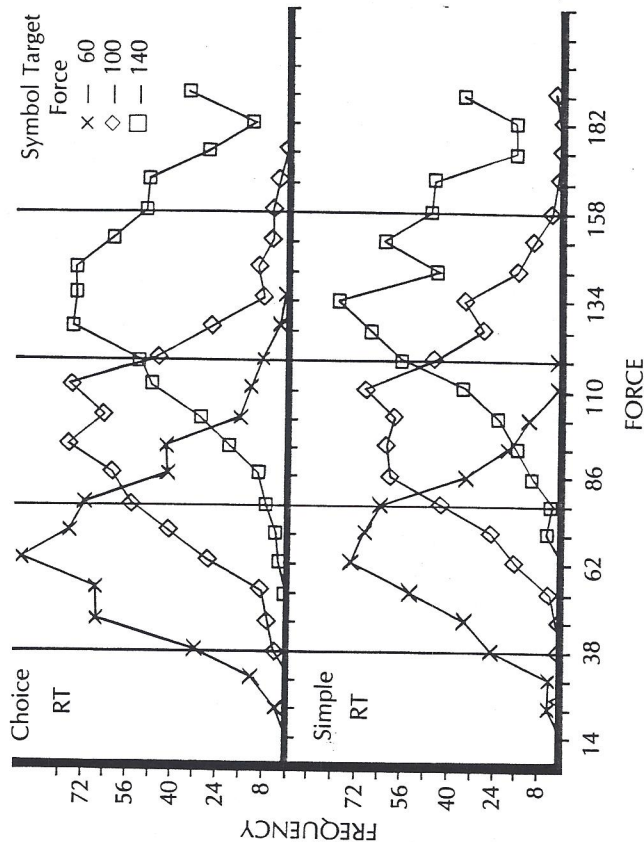
Results

Table 1 presents the means and mean standard deviations for response latency, maximum force, response duration, and time to peak force in both RT conditions. As shown in the second data column, the subjects' mean maximum force for each target level closely matched the target forces of 60, 100, and 140 in both the choice and simple RT conditions. The third and fourth data columns show that the movements themselves were extremely similar between the two RT conditions. Response duration and time to peak force increase more or less linearly with increases in force. This indicates that more time is required to make stronger isometric contractions. However, all of the responses were quite rapid, as indicated by the overall mean time to peak force of 90.7 ms and overall mean duration of 213.9 ms. Thus, the responses can all be considered ballistic, with time to peak forces being too short for feedback control (e.g., Poulton, 1981), and in this sense, qualitatively similar in terms of the timing demands.

The main data of interest are the response latencies. These scores were submitted to a 2 (RT Mode: Simple vs. Choice) x 3 (Target Force: 60, 100, 140) repeated measures ANOVA. Not surprisingly, the factor RT Mode was highly significant, $F(1,9) = 203.3, p < .001$, demonstrating that subjects were able to prepare at least some aspects of their responses in the simple RT sessions. More interesting, the main effect of Target Force was not significant, $F(2,18) = 2.04, p > .1$. The interaction between the two main effects approached significance, $F(2,18) = 3.33, .05 < p < .10$. The results of the ANOVA do not support a conclusion that response latency is a function of the force required. In fact, the 20 ms advantage for the two higher force levels in the choice RT condition was primarily the result of the data from two subjects who were approximately 50 ms faster on responses to the 100 and 140 force targets than to the 60 force targets.

Errors

As noted in the Methods section, preliminary testing showed the task to be rather difficult, and this was evident in the high error rates. The



(Each hashmark is the midpoint of a bin spanning 8 arbitrary units.)

Figure 2. Frequency distributions of the actual forces produced for each of the conditions in Experiment 1. Force measures are in terms of the arbitrary units of the A to D converter. Vertical lines indicate the boundaries between the different target forces.

overall error rate was 41.4% in the choice RT condition and 33.5% in the simple RT condition. Given such high error rates, it is first necessary to exclude the possibility that the subjects were responding in a near-random fashion. Specifically, the finding that latency did not vary as a function of target force may have been a consequence of the subjects' inability to distinguish between the three different force levels. Two aspects of the data argue against this possibility. First, although the error rates were high, chance performance would have predicted error rates of 80%, a figure well above the observed values. Second, the distributions of forces produced for each target force are quite distinct. Figure 2 shows that there is considerable overlap between the distributions. Unless the subjects performed perfectly, this would be expected because the targets shared boundaries. Nonetheless, there is little overlap between the distributions for the lowest and highest target forces, indicating that the subjects were sensitive to the different response categories.

A decomposition of the errors into slow starts and force errors for each condition is given in the last two columns of Table 1. As can be seen, the vast majority of these errors were due to subjects producing a peak force value that was either above or below the criterion force levels. This type of error is represented in the tail portions of the distributions in Figure 2. In the simple RT condition, 93.7% of the errors were of this type, and the analogous figure in the choice RT condition was 67.0%. Most of the remaining errors in the choice RT condition were due to slow starts (latency > 600 ms) and these were evenly distributed among the three different force levels. The same dispersion was not evident for the force errors in that the mean number of errors increased with larger target forces.

This last point leaves open the possibility that a trade-off between speed and accuracy may have contaminated the response latencies. However, two factors argue against such an interpretation. First, while the errors due to applying the wrong force were extremely similar across the two RT conditions, the fastest responses were for different force targets in the two RT conditions. Second, the error profiles were consistent across subjects within each RT condition, yet the latency profiles were dissimilar. In other words, there did not appear to be a correlation between the error patterns and the latencies, as would be expected if the subjects were engaging in a trade-off between speed and accuracy.

Supplementary Experiment

As noted above, the interaction between RT mode and Target Force approached significance. To test for the possibility that this interaction may have been obscured by the high variability both between and within subjects, a slightly modified supplementary experiment was conducted with 8 new subjects.

This supplementary experiment was designed to be a replication of Experiment 1. A few modifications were adopted to test whether the same results would be obtained under slightly different conditions.

Three force levels again served as response targets in both simple and choice RT conditions. However, lighter springs were placed in the strain gauge. This created a new range of target forces of approximately half the values, as had been used in Experiment 1.³ In addition, the criterion range for determining if a subject had made the correct response was increased to plus or minus 25 arbitrary units in an effort to reduce the high error rates. The range in arbitrary units for light contractions was 35–85, for moderate contractions, 85–135, and for strong responses, 135–185. Since the minimum displacement criterion corresponded to a value of 25 and the maximum response was 188, the three forces covered almost the entire range of the strain gauge.

The latency data were analyzed in the same manner as in Experiment 1. The results essentially replicated those of Experiment 1: Response latency did not vary as a function of force, and of greatest interest, the interaction between RT mode and Target Force did not approach significance, $F(2, 14) < 1.0$.

Unfortunately, the wider criterion ranges did not greatly reduce the error rates. The overall error rate in the choice RT condition was 37.4%; it was 34.0% in the simple RT condition. As in Experiment 1, most of the errors were due to subjects producing the wrong maximum force, and the error rates tended to increase for the higher target forces. Since the subjects were slowest and made the fewest errors in the same conditions (light contractions in both the simple and choice RT conditions), an explanation based on a trade-off between speed and accuracy may be valid. However, as in Experiment 1, the error profiles in the supplementary experiment were consistent across subjects, yet the latency profiles were quite dissimilar.

Discussion

Taken together, Experiment 1 and the supplementary experiment demonstrated that varying the intensity of an isometric contraction does not influence the time required to initiate the response. This pattern of results was observed in both simple and choice reaction time situations and across two different ranges of target forces. As demonstrated by the significantly longer RT's in the choice condition, different components of the response preparation period were being measured in the two RT conditions. That is, the long RT's in the choice condition reflected additional processing time. It cannot be determined whether this additional time was required for stimulus identification or response selection.

These findings replicate and extend the observations of Klemmer (1957), who obtained similar results in a simple RT experiment using two force levels.

The failure to find any differences in latency in the choice RT condition may appear to contradict the results of Ghez and Vicario (1978). They found that the reaction times for cats decreased with increases in force. Besides the differences in species tested and the question of whether the term "choice reaction" time can adequately be applied to

cats, a more concrete explanation can account for the ambiguity. The task in their experiment was to generate an appropriate amount of force to return a feeder to a center position. Deflection of the feeder served as the stimulus, and the speed of deflection indicated to the animal the amount of force required. As Ghez and Vicario (1978) (also Ghez, 1979) noted, stronger stimuli are generally responded to faster; thus, their target forces are confounded with stimulus intensity.

The results obtained in experiment 1 and the supplementary experiment with isometric contractions are also consistent with latency data recorded during isotonic movements in which force is varied (Glen-cross, 1972; Lagasse & Hays, 1973; Baba & Marteniuk, 1983).

What inferences can be drawn from these results in view of a theory of motor control that emphasizes that force and timing must be centrally programmed for ballistic movements? Since the mean times to reach peak force in Experiment 1 were all less than 115 ms, it can be concluded that the subjects had selected an appropriate force output level before initiating their responses. The lack of differences in latency profiles implies that the selection of an appropriate force level requires a constant amount of time. Because the data clearly show that the responses have been prepared in advance of the reaction signal in the simple RT condition, it also can be inferred that the time required to generate the neural signals to the muscles is also invariant across different force levels.

Experiment 2

Experiment 2 was designed to examine the other part of force-timing models of motor control—namely, Is response latency influenced by the duration of the intended movement? All of the responses were performed isometrically on a strain gauge, and the force required in the different timing conditions was held constant. However, the subjects were required to maintain their responses for a variable period of time. This method allowed us to study the influence of timing variation when all other aspects of the movement were held constant.

Similar manipulations have been performed in the past. Baba and Marteniuk (1983) held torque constant in a simple RT experiment with isotonic movements by allowing longer duration movements for heavier weights. They found that subjects took more time to initiate the longer movements. However, since extent was the same in all of their conditions, it can be inferred that the subjects performed the movements more slowly in the long duration movement condition. Another design has repeatedly been employed by Klapp and his associates (Klapp et al., 1974; Klapp & Rodriguez, 1982; Klapp & Greim, 1981). In those experiments, the subject was required to press a Morse key for either a short (100 ms) or long (300 ms) interval. In the original experiment (Klapp et al. 1974, Experiment 1), response latencies under both simple and choice RT conditions were significantly faster for the short responses. Those differences disappeared in the simple RT condition

when subjects were given extensive practice (Experiment 2). It is unclear, however, if providing subjects with a lot of practice is the best method for assessing motor-programming differences. Practice in such simple tasks may allow for the establishment of programs that bypass the normal processing paths.

There are other methodological and theoretical reasons to question the generality of Klapp's results. First, both Kerr (1979) and Klapp and Greim (1981) have demonstrated that the differences due to variation in timing disappear under certain feedback conditions. Second, in their original experiment, Klapp et al. (1974) required subjects to begin each trial by depressing the Morse key. Thus, their movements actually involved two phases—the subjects had to lift their finger up before reversing the movement to make their response. This adds an unwanted degree of complexity to the movement.

More important for our present purpose is the fact that the "long" duration movements in both the Klapp studies and the experiment of Baba and Marteniuk (1983) are actually quite short. In Klapp's studies, the "long" response is only 300 ms, whereas Baba and Marteniuk considered 220 ms movement durations as long. It is quite probable that all of the movements in these experiments were programmed in their entirety prior to movement onset. Thus, the latency profiles may only reflect quantitative programming differences. That is, all of these movements are ballistic in nature and only vary slightly in the speed in which they are executed. If longer duration movements are qualitatively different (i.e., the onset and offset of the movement are not both preprogrammed), as has been suggested by some authors (e.g., Desmedt, 1983; Meink, Benecke, Meyer, Hohne, & Conrad, 1984), a different pattern of results may emerge when a greater range of movement durations is tested. Klapp and Erwin (1976) did test a wider range of durations in a lever-moving task and found that choice RT's were consistently slower for movements of long duration. However, it can be inferred from their methodology that the initial velocity profiles were quite different between the various duration conditions. The present experiment was designed to avoid this confound.

Method

Apparatus

The apparatus was the same as in Experiment 1.

Subjects

Ten young adults were selected from the Cognitive Laboratory Subject Pool at the University of Oregon. Three of the subjects had participated in Experiment 1, whereas the remaining seven were new to this series of experiments. As before, all were right handed with normal or corrected-to-normal vision and hearing. The subjects were paid \$6.

Procedure

The procedure in both simple and choice RT conditions was essentially unchanged (see Figure 1). However, the movement requirements were different. Subjects were asked on all responses to generate a force of 7.5 N. This corresponded to a score of 100 on the arbitrary scale of the A to D converter. Force scores below 70 and over 130 were counted as incorrect and were followed by the error message "Out of Force Range." The stimulus set (0,1,2) was mapped to the responses in the following manner: Stimulus 0 required that the response duration be between 0 and 400 ms. This range was adopted in an effort to ensure that these responses were entirely ballistic. That is, to meet the task demands, the subjects would have to rapidly make a contraction and then release that contraction in order to negate their force output. Stimulus 1 required that the duration be between 700 and 1300 ms, and Stimulus 2 had a tolerance range that went from 1400 to 2600 ms. Both of these conditions were expected to require qualitatively different movements than the responses to the 0 stimulus. The subjects were required to make a single, rapid, initial contraction, as for Stimulus 0, but then they had to maintain that contraction for a variable period of time before release. As in Klapp and Erwin's (1976) experiment, the tolerance range for the two longer responses was set at plus or minus 30% of the target time. A proportion method was adopted following pilot testing. Any response durations that fell outside the respective boundaries were recorded as errors and were followed by the message "Out of Duration Range." The criteria from Experiment 1 were used to test for "Slow Starts" (latency > 600 ms) and "False Starts" (responding to the stimulus 4 in the choice RT condition or when a second tone was presented in the simple RT condition).

It was not possible to obtain a meaningful measure of time to peak force because a subject might slightly increase his/her force during the hold period, and the time at which the new maximum was achieved would be considered by the computer program as the time at which peak force was achieved. To ensure that the initial contractions across all conditions were similar, the instructions emphasized that responses should be made rapidly. Observations by the experimenter and the comments of the subjects during debriefing confirmed that this mode of responding was used. That is, in the hold conditions, subjects rapidly generated a target force and then maintained that force, rather than making ramped, gradual responses.

As in Experiment 1, 40 practice trials preceded the first test session for each RT condition. Two test sessions of 60 trials in each RT condition produced the data for analysis. The order of sessions was counter-balanced across subjects.

Results

Table 2 presents the means and mean standard deviations for response latency, maximum force, and response duration. As is evident in the sec-

Table 2
Means and Standard Deviations for Experiment 2

Time range	Stimulus	Latency	Force	Response duration	Slow starts	Force errors	Duration errors
		Simple RT condition					
Ballistic (400)	0	289 (58)	99 (16)	243 (44)	.00	.05	.02
700 - 1300	1	310 (63)	100 (12)	1035 (139)	.00	.02	.06
1400 - 2600	2	316 (68)	100 (13)	1859 (321)	.00	.02	.02
Means		305	100	—			
		Choice RT condition					
Ballistic (400)	0	462 (73)	97 (14)	254 (51)	.04	.04	.02
700 - 1300	1	451 (64)	101 (13)	1021 (142)	.02	.02	.05
1400 - 2600	2	455 (67)	99 (12)	1883 (224)	.02	.01	.02
Means		456	99				

Note. Force measures are in terms of the arbitrary units of the A to D converter, and the timing measures are in ms. Error rates are in terms of proportion of total trials for each RT condition.

ond data column, the mean force for each timing level closely matched the target force. It can thus be concluded that the initial movement was the same for all six conditions. The third data column shows that the subjects were, for the most part, successful in meeting the time requirements. Responses to the 0 stimulus were ballistic (mean RT = 248.3 ms). The subjects displayed a tendency to hold responses to Stimulus 1 for a longer time than the target time and an even greater tendency to shorten the interval on responses to Stimulus 2. However, considering the wide tolerance ranges, it appears that sufficiently different timing conditions were achieved.

The latency data were tested in a 2 (RT Mode: Simple vs. Choice) \times 3 (Target Time: Ballistic, 1000 ms hold, 2000 ms hold) repeated measures ANOVA. The main effect, RT Mode, was again highly significant, $F(1,9) = 53.92, p < .001$. As stated before, this demonstrates that some programming took place prior to the reaction signal. The main effect of Target Time approached significance, $F(2,18) = 2.88, .05 < p < .10$, and there was a highly significant interaction between these factors, $F(2,18) = 9.87, p < .001$. Post-hoc analysis was carried out via the Tukey method (overall $\alpha < .05$). This analysis showed that whereas the ballistic responses (Stimulus 0) were significantly faster than the hold responses (Stimuli 1 and 2) in the simple RT condition (average difference of 23.8 ms), no differences were observed between the three levels of target time in the choice RT condition. In fact, the mean latency score for ballistic responses in the latter condition were in the opposite direction (average

of 9.6 ms slower). Comparing the individual subject data for the ballistic condition with the average of the two hold conditions confirms this interaction. All 10 subjects were faster to respond ballistically in the simple RT condition, whereas only 2 were faster in the choice RT condition, 7 were slower, and 1 was the same.

Errors

The overall error rate was 26.9% in the choice RT condition and 21.6% in the simple RT condition. A breakdown of these errors into slow starts, force errors, and duration errors is displayed in the last three columns of Table 2. Except for the slow starts (latency > 600 ms), the error pattern was the same in both RT conditions. Specifically, while the percentage of force and duration errors differed between the three levels of Target Time, the order and magnitude were almost identical between the two RT conditions. As in Experiment 1, it seems difficult to invoke speed-accuracy hypotheses, for the same error pattern would have to explain different latency profiles.

As alluded to above, the slow starts were not evenly distributed among the responses in the choice RT condition: 12.3% of the ballistic responses resulted in this type of error, whereas only 7.4% of the 1000 ms hold or 2000 ms hold trials were similarly terminated. In light of this aberration, the data from the choice RT sessions were reanalyzed, but the criterion RT time was raised to 900 ms. (Since only 0.9% of the responses in the simple RT condition had latencies greater than 600 ms, a similar analysis was unnecessary for this condition.) This reanalysis showed that the difference in response latencies between the three levels of Target Time may have been somewhat obscured by the original, strict criterion. The new mean latencies were 487.9 ms, 467.3 ms, and 471.6 ms for the ballistic, 1000 ms and 2000 ms conditions, respectively.⁴ Although this post-hoc analysis must be treated cautiously, it lends further support to the hypothesis that, in the choice RT sessions, subjects were slowest when asked to make ballistic responses.

Discussion

Experiment 2 demonstrated that varying the timing demands of a movement can significantly affect the latency profiles. However, the significant interaction indicates that the effect may be differentially manifested as a function of different RT methodologies.

The results in the simple RT condition are conclusive and concur with the previous work of Baba and Marteniuk (1983). Subjects are slower to initiate longer duration responses. The evidence supports the hypothesis that more time may be required to prepare for and implement a response that requires the maintenance of a contraction. While the latency difference between the 1000 ms and 2000 ms hold conditions was not significant, the direction of the means suggests that real-time increases may require even longer program readout time. Alternatively,

programming timing instructions may not be a function of the real-time demands, but may reflect a qualitative distinction between rapid and maintained movements. Future testing with a greater range of target times will be necessary to distinguish between these alternatives.

Interpretation of the data from the choice RT conditions is less straightforward. While the mean latencies in this condition were not statistically different, the means of the individual subjects showed a consistent reversal between the two RT conditions. That is, the subjects were usually slowest to initiate the ballistic responses in the choice RT sessions. This result is especially puzzling if it is assumed that choice RT's encompass all of the preparation phases contained in simple RT's, plus some additional programming demands. It seems unlikely that the differences in time required to implement the motor program disappear in a choice methodology. This suggests that the additional programming demands in the choice RT condition obscure the latency gain found for ballistic responses in the simple RT situation. The following model shows how this may have occurred.

The structure of the model is sketched in Figure 3. There are two primary stages of response preparation in the model. The first stage, shown below the dotted line, involves three processes that are required to construct the motor program. The second stage, shown above the dotted line, represents those processes that are required for implementing the program. It is assumed that the subcomponents in the construction phase are assembled into a holding buffer. The abstract motor

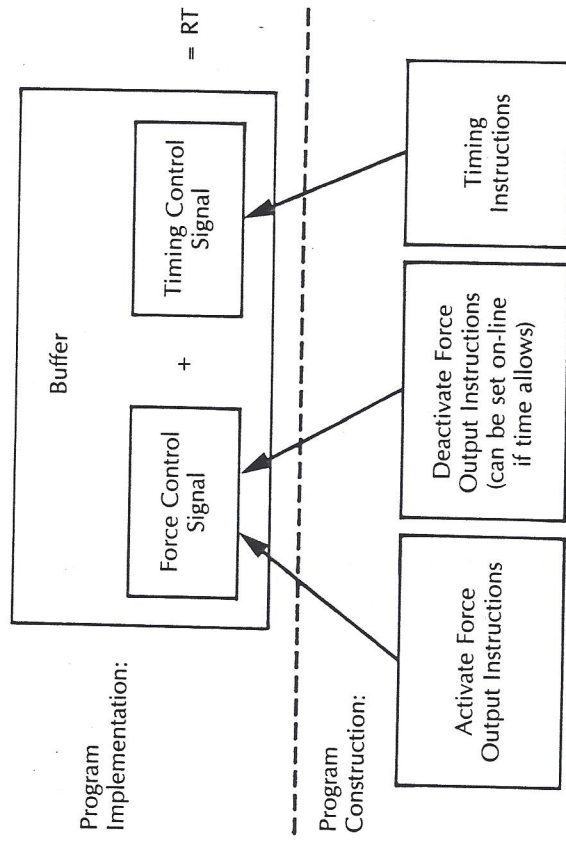


Figure 3. Model of the stages and subcomponents required to develop and implement a motor program for isometric contractions.

program is then transformed into the actual signals to be relayed to the muscles. Responses in simple RT conditions only involve the top stage of the model since the program can be constructed in advance of the reaction signal. However, in the choice RT conditions, the respondent must work through both stages.

How does the model account for the results of the first two experiments? First, the finding that the subjects were slower in the simple RT condition of Experiment 2 for the 1000 ms and 2000 ms responses than for the ballistic responses is explained by the hypothesis that less time is required to implement a program when there is no value assigned to the timing-control component. It may be that the buffer holds less information and thus can be readout more quickly. Another possibility is that the time required to readout the timing instructions may be a function of the real time demands of the task, with shorter responses requiring less time. This possibility is suggested by the nonsignificant increase in latency across RT conditions for the 2000 ms responses in comparison to the 1000 ms ones. Second, the finding that latencies in the choice RT condition for ballistic responses tend to be slower than for the longer duration responses is also accounted for by the model. The force control component in the buffer is the product of two subcomponents—setting force activation and setting force deactivation. It is assumed that when the response is of sufficient duration, the instructions for deactivating the force can be set after the response is initiated. Thus, the two longer responses in the choice RT condition can be initiated faster since the deactivation subcomponent of the construction stage is bypassed. This is not possible for the ballistic responses since the time interval between activation and deactivation is too short to allow the subject to construct the deactivation phase on-line.

The finding in Experiment 1 that latency did not vary as a function of force is also accounted for by the model. All of the responses in Experiment 1 are qualitatively similar and thus entail the same processing subcomponents and buffer structure. Specifically, the timing parameter is set to 0 for all of the responses since the subjects had to rapidly contract and release their muscles in order to meet the task demands. This requires the subjects to set both the activation and deactivation instructions prior to making their response. Note that the time demands for either of these components is assumed not to depend on the quantitative requirements of the different tasks. Furthermore, the model proposes that when both the activation and deactivation of force output are set, they combine to form a single component in the buffer.

This last assumption leads to a prediction of the model. If the timing requirements are held constant, subjects should be slower in a choice RT task when a response involves both force activation and deactivation, in comparison to responses that only require programming of force activation. However, the same result should not be evident in a simple RT task because these two subcomponents have been merged into a unitary component in the buffer prior to the reaction signal. Experiment 3 tested this prediction.

Experiment 3

All of the responses in Experiment 3 were ballistic in the sense that the timing demands did not allow the subjects to maintain a contraction. Thus, timing control was held constant by requiring its value to be set to 0 for all of the responses. The number of subcomponents (1 or 2) required for force control was varied by using two different responses. The first type of response was designed to entail only the programming of force activation by having the subjects push maximally on the key press. In such a condition, subjects can clearly feel when the strain gauge has reached a maximum compression point. Thus, deactivation of these movements is externally signalled; therefore, it is assumed that programming the deactivation phase can be bypassed. For the other type of response, the subjects were required to make a key press that was less than maximal. In order to avoid the possibility that these responses would involve accuracy demands that were not involved in the maximal responses, the subjects were allowed to make presses that covered almost the entire range of the strain gauge.

As stated above, the model predicts that response latencies should be faster in the choice RT condition for the maximal condition since the deactivation component can be bypassed, whereas no differences should be obtained in the simple RT condition. More specifically, the magnitude of the expected RT difference between the two types of responses can be estimated from Experiment 2. In that experiment, ballistic responses were an average of 23.8 ms faster than the longer duration responses in the simple RT condition. However, these same responses were an average of 9.3 ms slower in the choice RT condition. If it is assumed that the gain in latency when there is no timing requirement was the same across the two RT conditions, but that the gain in the choice condition was obscured by the time required to program the deactivation component, then a rough estimate of the time to generate the deactivation instructions is 33.1 ms ($23.8 + 9.3$).

Method

Apparatus

The apparatus was the same as in the previous experiments.

Subjects

Ten subjects were selected from the Cognitive Laboratory Subject Pool at the University of Oregon. Three subjects had participated in at least one of the first two experiments. All were right handed with normal or corrected-to-normal vision and hearing. The subjects were paid \$6.

Procedure

The procedure was the same as in Experiment 1. However, only two different force ranges were tested. The maximal force trials required responses in which the response key was pressed with sufficient force to

Table 3
Means and Standard Deviations for Experiment 3

Force range	Stimulus	Latency	Force	Response duration	Time to peak force	Slow starts	Force errors
	Simple RT condition						
40 - 160	0	248 (53)	86 (24)	184 (28)	78 (20)	.00	.02
Maximum (188)	1	241 (55)	188 (-)	282 (34)	71 (21)	.00	.03
Means		244	-	233	75		
	Choice RT condition						
40 - 160	0	441 (77)	84 (24)	191 (37)	81 (26)	.04	.03
Maximum (188)	1	410 (69)	188 (-)	290 (43)	75 (27)	.02	.03
Means		425	-	240	78		

Note. Force measures are in terms of the arbitrary units of the A to D converter, and the timing measures are in ms. Error rates are in terms of proportion of total trials for each RT condition.

completely compress the springs (minimum force required was 13.9 N). Trials were counted as correct in the other force condition if a score on the arbitrary scale was between 40 (3.0 N) and 160 (12.0 N). This included most of the possible range of the strain gauge. The subjects were not instructed to shoot for any particular force level in this latter condition; rather, they were told to "feel free to use any force level which fell in this range." The digit 0 was matched to this condition and the digit 1 was used as the stimulus for the maximal responses. Absence of a second tone in the simple RT condition and the presence of the digit 4 in the choice RT condition were included for catch trials. Response latencies were again required to be below 600 ms, and response durations shorter than 400 ms.

Ten correct responses to each stimulus constituted a practice block, and 20 similar responses were required in the test session. As before, the ordering of simple and choice RT conditions alternated. Half of the subjects started with a simple RT session, whereas the other half began with a choice RT session. Unlike the earlier experiments, time permitted three test sessions of each RT condition. Hence, each subject produced 60 data points for analysis at each of the two force levels for both RT conditions.

Results

Table 3 presents the means and mean standard deviations for response latency, maximum force, response duration, and time to peak force. The latency data were entered into a 2 (RT Mode: Simple vs. Choice) \times 2 (Target Force: 40-160 vs. Maximal) repeated measures ANOVA. As

before, subjects were considerably faster in the simple RT condition, $F(1,9) = 568.36, p < .001$. More important, the main effect of Target Force was also significant, $F(1,9) = 7.79, p < .025$. Unexpectedly, the interaction of these two factors only approached significance, $F(1,9) = 3.66, .05 < p < .10$. The responses for the maximal press trials were faster in both the simple and choice RT conditions. However, the magnitude of the differences does support the model. The average gain in latency in the choice RT condition was 31.6 ms, whereas it was only 7.1 ms in the simple RT condition. The latency difference of 31.6 ms in the choice RT condition closely approximated the predicted value of 33.1 ms.⁵

The error rates indicated that these tasks were considerably easier than in the previous experiments. The overall error rates were 14.5% and 8.7% in the choice and simple RT conditions, respectively. The percentage of slow starts and force errors for each condition is shown in the last two columns of Table 3. The number of responses that were out of the force range did not differ between the two target forces. This can be interpreted as validating the assumption that the inclusion of a wide force range did not impose any asymmetric accuracy demands. Indeed, the only large difference in errors between the two target forces was that more slow starts were recorded for the 40-160 condition in the choice RT paradigm. A similar reanalysis of the data as reported in Experiment 2 was performed with a latency maximum of 900 ms. This increased the mean gain in latency for the maximal force responses to 42.3 ms.

Discussion

Overall, the results of Experiment 3 supported the programming model described above. The subjects were considerably faster in initiating responses under choice RT conditions when a signal to terminate force output was externally indicated upon reaching the maximal excursion of the strain gauge. The model postulates that, under such conditions, time can be saved in the response-preparation phase by bypassing the deactivation component in the program-construction stage. Instead, deactivation occurs on-line when maximum force is externally signalled. A similar shortcut can not be taken when the deactivation of force output must be internally controlled by the subject in that the deactivation component must be preprogrammed.

Contrary to our prediction, however, the interaction between RT mode and target force only approached significance. It is unclear why this interaction did not surface statistically. It may be that in a small percentage of the trials, subjects did not preprogram their responses and this contributed to the small differences in response latency in the simple RT condition. On the other hand, the assumption that force activation and deactivation are combined into a single component in the buffer may be incorrect (but see Note 5). The greater magnitude of the latency difference in the choice RT condition, however, supports the hypothesis that the time requirements of the deactivation process are most evident in the program-construction stage.

The experiments reported in this paper have focused on the effects of force and timing variations on the response latency in isometric finger movements. As in most experiments involving chronometric methods, it is assumed that changes in response latency reflect the extent of processing required prior to response initiation. More specifically, in the present study, reaction times are assumed to indicate the degree of complexity of a hypothetical mental representation, the motor program. This approach has certainly been embodied in a large body of previous research (e.g., Rosenbaum, 1980; Larish & Frekeny, 1985). However, these studies have frequently compared variables that may be subsumed under a common process. For instance, selection of hand and direction have been treated independently, but may be part of a single muscle-selection process. The basic premise guiding current research is that a necessary first step for developing a definition of "complexity" requires a thorough description of how complexity is manifested in the simplest movements. Research that is designed to look at the components of more involved motor programs will only be fruitful when the basic operations have been defined more concisely. Furthermore, elucidation of these operations may allow researchers to identify underlying neural systems (Ivry & Keele, 1986).

The results indicate that program complexity does not vary as a function of the force required in an isometric contraction. The time required to prepare and generate a desired output level of force is invariant across the range of forces examined. The parameterization of timing, however, is a function of the real-time demands of the movement. The present study suggests that the discrete presence or absence of timing is one parameter. In addition, if timing is necessary, then its programming time may depend on the length of movement time, as suggested by Klapp and Erwin (1976) and hinted at by the nonsignificant RT difference in Experiment 2 between the 1 s and 2 s response duration movements. As Klapp and Erwin (1976) have argued, control of longer movements may involve longer neural circuits in order to provide the required time delays between the components of the response.

This asymmetry in the processing demands for setting the parameters of force and timing provides only indirect evidence for the hypothesis that the two variables are independently controlled. More direct support would require a comparison between conditions in which both of these factors may vary. However, data collected during the execution of movement have generally supported the notion that force and timing are independently controlled (e.g., Freund, 1983; Ghez, 1979). It would seem most parsimonious that the preparatory processes would mirror this independence.

Perhaps the most surprising aspect of the data reported here is the finding that all ballistic responses cannot be treated as a homogeneous group in terms of the processing demands they entail. Ballistic responses in which the subject must control the deactivation of force output in-

volve a more complex motor program than similar responses in which a signal to terminate force output is externally provided. Although it has been widely suggested that different control strategies are involved in ballistic and ramped movements (e.g., Hallett, Shahani, & Young, 1975; Brown & Cooke, 1981), the hypothesis that subjects can employ different control strategies for ballistic responses has only recently been advanced. Most of this research has been designed to test the conjecture that the antagonist component of the biphasic and triphasic bursts typically seen in EMG recordings during ballistic responses serves as a braking mechanism. Meinck et al. (1984) observed this triphasic activity in rapid isometric movements and found that only the second agonist burst was eliminated in isometric movements of similar magnitude. However, the antagonist activity also disappeared when subjects were instructed either to relax their finger passively after responding or to maintain the response for 1 s. The parallel between this last condition and Experiment 2 is obvious. A design similar to Experiment 3 was used by Waters and Strick (1981), who found that the antagonist burst was considerably reduced and even abolished when ballistic responses were terminated by a mechanical stop (see also Marsden, Obeso, & Rothwell, 1983). Other researchers (Conrad & Brooks, 1974; Vilas & Hore, 1981) have found that cerebellar cooling in primates primarily disrupts the activity of the antagonist muscles. After cooling, the antagonist is generally evident only after a mechanical stop is contacted, rather than before contact as is found with normal primate subjects. Thus, following cerebellar dysfunction the antagonist activity appears to have switched from a braking mechanism to a feedback response.

It would be premature to conclude that the deactivation component of the motor-programming model postulated in this paper directly corresponds to the subsequent activity of the antagonist muscle. However, the finding that a change in response strategy leads to significant changes in both latency and EMG response programming and response execution is promising. A study that will examine both measures currently is presently being planned.

NOTES

1. As one of the reviewers has pointed out, the term "timing" has been used in a number of different ways in the motor-control literature. In this paper, time has been defined as events that can be measured on an interval scale such as number of ms. Another use of timing refers to the temporal pattern of a sequence of muscular actions. When this latter definition is employed, the emphasis is usually on the proportional durations of different phases of a movement (e.g., Kelso et al., 1979). Timing in this sense may only be a consequence of the kinematic events. However, it is quite clear from rhythm studies (e.g., Wing, 1980) that people can explicitly control the real-time events required in a series of movements. Thus, it is reasonable to assume that the long movements studied in Experiment 2 must be under some form of explicit timing control. Whether such control is involved in ballistic movements remains an open question.

2. Throughout this paper, the term *movement* is applied to the isometric responses of the subjects. This may seem misleading, for the actual movement is minimal (only the

slight compression of the springs); the movement of concern involves a change in muscle tension.

3. Due to a subsequent change in the calibration settings of the apparatus, the actual force values are unavailable.

4. A similar reanalysis of the data from Experiment 1 showed that, although the latencies were inflated, the differences between the different force levels remained unchanged.

5. The 7.1 ms gain in the simple RT condition may be an artifact of our measurement method. The time to peak force is approximately the same for both target forces. Thus, the velocity (and acceleration) must be greater for maximal responses since a larger force is generated in the same amount of time. This implies that the time from which the subject actually began to press to when he actually reaches the criterion point at which response initiation is recorded is less for the maximal responses. Data produced by the experimenter indicate that the size of the artifact is between 4 and 8 ms. This same artifact may explain why in three of the four RT conditions of Experiment 1 and the supplementary experiment, subjects were slightly faster on the large force trials in comparison to the small target force. It should be noted that this artifact would also have inflated the difference in mean latency in the choice RT condition of Experiment 3. If this artifact is actually present, a better estimate of the time required to program deactivation commands would be 24.5 ms. (Subtracting the 7.1 ms difference obtained in the simple RT condition and, thus, an estimate of the size of the artifact, from the 31.6 ms difference in the choice RT condition.)

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A Note on Modulations and Structuring of Locomotion in Children and Adults

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ABSTRACT. The aim of this study was to investigate the modulations of locomotion induced by a rhythmic cognitive task (counting one's steps). Subjects (6- and 8-year-olds and adults) were requested to walk freely, and then to walk while counting their steps. Here a decrease in cadence values was observed in children only, with quasi-total repercussions on velocity at the age of 6 only. The spatio-temporal structuring of locomotion described here is already present at 6 years of age and is not altered in the step-counting situation: strong links were observed between cadence and velocity, and between stride length and velocity, and weak links between cadence and stride length.

LOCOMOTION CAN TAKE various forms from one species to another (limb alternation in walking, wing-phase movement in flying, natarorial or reptilian body undulations), but they are all characterized by rhythmicity (Delcomyn, 1980; Grillner, 1981; Shik & Orlovski, 1976). This rhythmicity is what gives locomotor automatism its high degree of regularity. Bernstein (1967) has pointed out four salient aspects of locomotion in humans: (a) "it is both a stable and typical structure, incorporating many dozens of characteristics for each normal subject"; (b) It is a "phylogenetically extremely ancient movement" well mastered by the species; (c) It also has had time and sufficient practice to be mastered individually; and (d) It is automatic in nature, which sets it apart from professional skills. He shows what a useful movement it can be to study, not only because of its repetitive nature but also because it allows us to "adopt constant criteria for the discrimination of the random from the regular."

From a developmental point of view, locomotion takes a long time to be acquired by children, whereas in most species, babies are able to walk and run some days or even some hours after birth. The rhythmic pattern seems to be set very early in infancy (stepping), before evolving to mature erect locomotion (for an overview of studies on this topic, see

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