Deceleration Requirements and the Control of Pointing Movements

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Deceleration Requirements and the Control of Pointing Movements

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ABSTRACT. When a limb is moved from one position to a target object, the limb and the target frequently collide. Often, the goal of the movement is to strike the target with a particular magnitude of impact. For single-aiming movements, impact forces have been shown to increase systematically with both an increased movement amplitude and a decreased movement time, thus providing deceleration to the moving limb. Models of speed-accuracy trade-off, however, have neglected to account for the contribution of these impact forces in the control of accurate movements. The aim of this experiment was to examine the modifications in the control strategy as a function of the amount of impact force a subject is allowed to use in decelerating his or her limb. Results showed that the structure of the acceleration-time functions was dictated by the amount of impact force subjects were allowed to use in decelerating the limb. Movement endpoint variability decreased as more impact force was used. The experiment suggests that the impact with a target is an important contributor to the deceleration of the moving limb and a critical determinant of movement organization.

Key words: impact force, motor control, movement variability, rapid movements

Several investigators have suggested that motor performance is often dictated and regulated by constraints on the decision system (Kerr, 1983) or on the musculoskeletal and neural structures (Kelso & Schöner, 1988; Kerr, 1983; Mackenzie & Martinü, 1985; Martinü, Mackenzie, Jeannerod, Athenes, & Dugas, 1987; Nelson, 1983). When a person moves a limb from one position to a target object, speed and accuracy are two such constraints that can affect the performance. Generally, it has been shown that fast movements can be made only at the expense of reduced spatial accuracy; conversely, accurate movements can be made only at the expense of reduced speed (e.g., Fitts, 1954). Some exceptions to this effect, however, have been demonstrated (Newell, Carlton, & Carlton, 1982; Schmidt & Sherwood, 1982). Many models have attempted to identify the control processes underlying these speed-accuracy trade-offs. Explanations in terms of the availability of visual feedback (e.g., Crossman & Goodeve, 1983; Keele, 1968), the variability of the muscular system (Meyer, Smith, & Wright, 1982; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979), as well as a "hybrid" model in which both visual control and muscular variability are responsible for aiming accuracy (Meyer, Abrams, Kornblum, Wright, & Smith, 1988) have been presented.

These models, however, have often overlooked what might be an important characteristic of rapid aimed movements: the impact with a target object. Often, not only is there a collision with the target object, but the goal of the task is to maximize or to control the magnitude of this impact. Recently, Teasdale (1987) has reported that for single-aiming movements, the peak impact force, on average (for movements of 10, 20, and 30 cm), increased 205% as movement time decreased from 240 ms to 160 ms, and 287% as amplitude increased from 10 to 30 cm. Similar results have been presented by Zelaznik, Schmidt, and Gie len (1986). These effects show clearly that impact forces occur in aiming tasks and that they presumably contribute to the deceleration of the moving limb.

Impact forces have also been shown to provide deceleration for the moving arm in slower movements (Martinü et al., 1987; Soechting, 1984; Waters & Strick, 1981; Worthingham, 1987). Given that the impact with a target area can provide deceleration for the arm, it is likely that the impact with a target is an important determinant of movement organization. Indeed, there is suggestion in the literature that movement control is affected by specific deceleration requirements.

Previous authors have examined the effects on movement trajectories of varying the size of a target (Martinü et al.,

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1987; Soechting, 1984; Worringham, 1987) and the nature of an object to be reached (Marteniuk et al., 1987). Generally, these experiments have shown that increasing the accuracy requirements through a decreased target size and/or an increase in the task’s functional demands (e.g., aiming vs. reaching and grasping) resulted in movements characterized by a lower velocity at target contact (hence, impact), a longer deceleration phase, as well as a decreased trajectory variability. Such results suggested to Marteniuk et al. (1987) that a longer deceleration phase and low velocity at target contact were characteristics of movements that had a more precise and controlled target approach. Because sensory information processing and corrections take time, subjects were thought to reorganize the movement so that deceleration phases were longer. In these experiments, however, movements that had low velocity at target contact also tended to have longer movement times (MTs). Thus, the decrease in variability in these experiments could also stem from a speed-accuracy trade-off.

There is, however, an alternative explanation for the increased duration of the deceleration phases. If the task imposes some impact constraints, the increased duration of the deceleration phase does not necessarily represent a change in the amount of sensory information utilized; rather it can be a consequence of principles of Newtonian mechanics. The reason is that, when high velocities at impact are allowed, a substantial part of the deceleration of the moving limb is provided by the impact with the target object. On the other hand, when a small impact magnitude is indirectly imposed on the movement, nearly all the forces responsible for the deceleration of the limb are muscular. Thus, the changes in the structure of the acceleration-time functions reflect changes in the deceleration requirements indirectly imposed by impact requirements of the reached object (as in Marteniuk et al., 1987) and may not reflect a different use of the sensory information available. If the impact magnitude is kept constant, however, changes in the duration of the deceleration phase could be an indication of a different use of the sensory information available. The aim of the present experiment was to examine such a possibility and to determine how movement control is affected when subjects are required to hit a target with a small (2 kg-19.62 N) or a large (8 kg-78.48 N) impact magnitude. Fast (250-ms) and slow (500-ms) movements were also used to generalize the results across movement durations.

Methods

Subjects

Four subjects participated in the three-session experiment. None was aware of the purpose of the experiment, and none had previous experience with the task. Subjects were recruited from an undergraduate class and received extra credit for their participation.

Apparatus

In Fitts-like movements, errors of stopping are measured in the same axis as the most important trajectory of the hand movement; therefore, the stopping or deceleration components and the aiming components of the movement are confounded. In order to allow a distinction between the aiming and the deceleration components of the movement, we studied a straight-line movement of the hand along the anterior-posterior plane. In such a movement, the errors are measured at right angles to the direction of the hand, and therefore, all variable errors can be thought of as errors of aiming (Howarth & Beggs, 1985). A three-dimensional lever apparatus was built to record the movements. Briefly, a vertical axle (9.5 mm in diameter) was supported by two pillow blocks attached on an aluminum plate (30 cm x 60 cm x 6.35 mm). A U-shaped aluminum block (90 mm x 60 mm x 25.4 mm) was attached to the upper end of the vertical axle. A precision angular potentiometer (Beckman Model 3351) was connected to the lower end. An axle (4.76 mm in diameter) was passed horizontally through the two legs of the U-shaped aluminum block, and another potentiometer was attached to one of its extremities. A linear potentiometer (Bournes), allowing a displacement of 50 cm, was secured on the horizontal axle. The lever system also included a handle with a stylus that was attached to the end of the sliding rod of the linear potentiometer. The information obtained from the three potentiometers was reconstructed through simple trigonometric transformations in order to obtain the three-dimensional cartesian position of the handle tip with reference to the center of rotation of the apparatus.

The handle was specifically designed to record impact forces. Strain gauges, used in a simple DC Wheatstone bridge arrangement, were mounted on it. The gauges were located on two plates, on each side of a center axis, and were oriented to measure forces parallel to the major direction of travel. A calibration session showed that the bridge was linear within the range of interest (0–12 kg).

The whole lever system was bolted to the reinforced upright platform of a standard chair. The point of intersection of the vertical and horizontal axes of rotation was just behind the right shoulder of the subject (0.200 m from the midline of the chair and 0.750 m above seat level). The initial position of the tip of the stylus was 47 cm from the point of intersection of the vertical and horizontal axes of rotation. An arm rest was secured to the right of the chair, under the lever system. A square aluminum target (20 cm²) was secured on a wall and surrounded by a piece of green cardboard (40 cm²); a small red light was affixed on the cardboard, 25 cm over the center of the target. The target and the lever system were aligned so that, from the initial position, a straight line in the seated subject’s sagittal plane would be the shortest distance to the center of the target. In that position, the tip of the stylus was 31 cm from the center of the target.

A washer-like conductive plate was attached on the mounting case of the linear potentiometer and allowed the sliding rod of the potentiometer to move freely. In the initial position, the handle was electrically connected to the plate. Moving the handle from the plate sent a pulse to the labo-
Control of Pointing Movements

The onset of the pulse determined movement initiation in the sagittal plane, and all the recorded data were synchronized with respect to this event. The onset of the impact force-time curve from the stylus determined movement termination. Thus, MT was defined as the interval between the onset of the voltage pulse and the sharp upswing of the impact-time curve. Because of the nearly instantaneous rate of change in voltage when a movement is initiated, such a procedure allows for the precise determination of movement onset without the possible confounding effect of variations in the initial rate of change of displacement. The signal from the linear potentiometer was amplified (Grass 7DA driver). All signals were digitized at 250 Hz.

Task
The subject's task was to begin with the tip of the stylus at a starting position (indicated by a pointer secured on the chair) and to move as accurately as possible to the center of the target. Further, subjects were required to move within ±10% of the goal MTs (250 and 500 ms). They also had to hit the target with a small (2 kg ± 15%) or a large (8 kg ± 15%) impact magnitude, in separate conditions.

Procedures
The procedures used for the three experimental sessions were similar. A brief description of the task was first presented, and subjects were required to move as accurately as possible to the target in various movement times and impact-magnitude conditions. Each trial started with the presentation of a red warning light. It signaled the subject to position the tip of stylus at the starting position. The red light was turned off 2 s later; subjects were then required to initiate their movement within the next 2 s. Reaction time was neither measured nor stressed. During practice trials, quantitative temporal and impact feedbacks were given after every trial. For the experimental trials, temporal feedback was provided only if subjects moved outside ±10% of the goal MT, and subjects were told to move faster or slower on the next trial. Similarly, impact feedback was provided if subjects hit the target outside ±15% of the goal impact-magnitude requirement, and subjects were told to hit the target with more or less impact on the next trial. There was an 8-s intertrial interval.

In each of the three sessions (conducted on separate days), the amplitude of the movement was kept constant at 310 mm across all the experimental conditions. There were two MTs (250 and 500 ms) and two impact-magnitude conditions (19.62 and 78.48 N), forming four experimental conditions. The order of presentation of the different conditions was counterbalanced across subjects and was different for each session. For each experimental condition, 15 practice trials were first given. After this practice, experimental trials were collected until 40 trials met the MT and impact-magnitude requirements.

Data Analysis
Data for trials in which the goal MT and/or goal impact magnitude were not achieved were not included in the analyses. Raw data obtained from the three potentiometers were filtered twice (forward and backward directions) with a Butterworth, second-order, low-pass filter with a cutoff frequency of 8 Hz. This procedure results in a fourth-order, zero-phase shift filter with a cutoff frequency of 6.4 Hz (Oppenheim & Wilsky, 1983; Winter, 1979). Simple trigonometric functions were used in order to obtain three-dimensional cartesian displacement-time coordinates of the stylus's tip. The displacement signals were then differentiated numerically twice with a central finite difference technique to obtain velocity- and acceleration-time curves. This technique has been shown to provide valid estimates of first and second derivatives (Pezzack, Norman, & Winter, 1977; Van der Meulen, Gooskens, Denier van der Gon, Gielen, & Wilhelm, 1990; Wood, 1982) and is thought to attenuate movement components possibly associated with physiological tremor (Stein & Lee, 1981) or oscillations originating from the mechanical characteristics of the arm (Van der Meulen et al., 1990; Walter, 1985). Values for kinematic measures of interest were determined using an interactive graphics program.

Results
In this experiment, a straight-line movement of the hand along the anterior-posterior axis was the shortest distance between the starting and the target position. Not surprisingly, the movement excursions along the medial-lateral and the inferior-superior axes were minimal. For example, for the 250-ms movements, the average (across-subject) excursions along the medial-lateral and the inferior-superior axes were 6.1 mm and 10.1 mm, respectively, which was minimal compared to the 310 mm separating the initial position from the target. Further, the structure of acceleration-time functions in the medial-lateral and inferior-superior axes varied from trial to trial, and no consistent pattern was revealed. For this reason, no further reference to the velocity- and acceleration-time data obtained along these latter axes will be made.

Acceleration-Time Functions
Representative acceleration- and impact-time traces along the anterior-posterior axis for the two different conditions of impact-magnitude requirement and the two conditions of MTs are presented in Figure 1. The different traces are from the first session of practice and from the same subject. For the 250-ms movements (top), the traces for the small impact-magnitude condition had a single peak of acceleration, whereas the large impact-magnitude condition had two peaks of acceleration. For the 500-ms movements (bottom), the acceleration-time functions obtained for both the small and the large impact-magnitude conditions had two peaks of acceleration. Such results were observed in all four subjects and for all three sessions of practice.

The different analyses yielded no practice effect and, as a result, data obtained for the three sessions were pooled.
The average across-subject values for the temporal locations and amplitudes of the different peaks of acceleration are presented in Table 1. For the 250-ms movements, the first peak of acceleration observed when a large impact magnitude was imposed had a temporal location similar to that seen when a small impact magnitude was imposed (167 vs. 164 ms), but its amplitude was much smaller (1,541 vs. 2,426 cm/s²). The second peak of acceleration occurred 56 ms before the impact and was similar in amplitude to the first peak (1,474 cm/s²).

For the 500-ms movements, the temporal locations of the first peaks of acceleration were similar (424 vs. 423 ms for the small and large impact magnitude, respectively). The second peak of acceleration occurred closer to the impact when a large impact magnitude was imposed than when a small impact magnitude was imposed (52 vs. 73 ms). The amplitudes of the first peaks were also similar (643 vs. 673 cm/s² for the large and the small impact-magnitude conditions, respectively). The amplitude of the second peak of acceleration, however, was more than 10 times larger when the impact magnitude was large than when it was small (1,618 vs. 129 cm/s²).

The spatiotemporal patterns associated with the differences observed in the structure of the acceleration-time functions were examined by determining the spatial position of the stylus at different temporal locations. Four arbitrary temporal locations (200, 150, 100, and 50 ms before the impact) were selected for that purpose. The data obtained were submitted to a 2 × 4 × 3 (Impact Magnitude × Temporal Location × Session) analysis of variance (ANOVA), with repeated measures on the three factors. At a given time from target contact, the stylus was always spatially closer to the target when the impact-magnitude requirement was small than when it was large—on average, 78 mm closer; \( F(1, 3) = 46.93, \ p < .01 \). For the four temporal locations analyzed, the subjects were respectively...

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TABLE 1
Amplitude and Temporal Location of the Peaks of Acceleration for the Different Movement Time and Impact Conditions

<table>
<thead>
<tr>
<th></th>
<th>Amplitude (cm/s²)</th>
<th>Temporal location (ms before impact)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1st peak</td>
<td>2nd peak</td>
</tr>
<tr>
<td>250-ms, large impact</td>
<td>1541 (387)</td>
<td>1474 (465)</td>
</tr>
<tr>
<td>250-ms, small impact</td>
<td>2426*</td>
<td>170 -</td>
</tr>
<tr>
<td>500-ms, large impact</td>
<td>643 (241)</td>
<td>618 (647)</td>
</tr>
<tr>
<td>500-ms, small impact</td>
<td>673 (208)</td>
<td>129* (355)</td>
</tr>
</tbody>
</table>

Note. Between-subject standard deviations are given in parentheses.

*Indicates that, for a given MT, the difference between the small and large impact conditions is statistically different. (\( p < .05 \)).
100, 110, 76, and 26 mm closer to the target when the impact-magnitude requirement was small than when it was large, \( F(3, 9) = 95.84, p < .001 \).

Similar results were obtained for the 500-ms movements. The stylus was on average 98 mm closer to the target when the impact was small than when it was large, \( F(1, 3) = 68.90, p < .005 \). For the four temporal locations analyzed, the subjects were 138, 127, 89, and 39 mm closer to the target when the impact magnitude was small, \( F(3, 9) = 20.91, p < .001 \). Hence, independent of the temporal requirement, compared to imposing a large impact magnitude, a small impact magnitude forced the subjects to be, at any given point in time, spatially closer to the target.

**Acceleration and Deceleration Durations**

To quantify some of the asymmetries in the acceleration-time curves and to determine how the durations of the acceleration and deceleration phases were affected by the different deceleration requirements, MT requirements, and practice, we computed a ratio of the duration of the acceleration phase divided by the duration of the deceleration phase. The acceleration phase was defined as the interval between the onset of the movement in the anterior-posterior plane to the temporal location of peak velocity in the same plane. The deceleration phase was defined as the interval from peak velocity to target contact. Asymmetries in the duration of the two phases were indicated by a ratio different than one. The ratios obtained for the different impact and MT conditions (averaged across days and subjects) are presented in Table 2. The results were submitted to a \( 2 \times 2 \times 3 \) (MT \( \times \) Impact Magnitude \( \times \) Session) ANOVA, with repeated measures on all factors.

For both conditions of MTs, the durations of the acceleration and deceleration phases were influenced strongly by the impact requirements. On average, the ratio was 6.9 when a large impact magnitude was imposed and 1.7 when a small impact magnitude was imposed, \( F(1, 3) = 59.04, p < .005 \), for the main effect of impact. The ratios tended to be larger for the 500-ms movements than for the 250-ms movements (5.2 vs. 3.3), but this difference was not statistically significant, \( F(1, 3) = 2.90, p > .05 \). With practice, there was also a tendency for the ratio to increase (from 3.6 on Day 1 to 4.6 on Day 3), but this difference failed to reach significance, \( F(2, 6) = 0.90, p > .05 \). Overall, the durations of the acceleration and deceleration phases were affected only by the impact requirements.

**Movement Variability**

The within-subject variability of the movement endpoints about the subject's own mean along the medial-lateral and the inferior-superior axes (\( W_{eX} \) and \( W_{eY} \), respectively) were computed to evaluate the possibility that subjects can increase their movement consistency by using the impact with a target to decelerate their limb. The average (across-subject) \( W_{eX} \) and \( W_{eY} \) are presented in Figure 2. The results obtained were submitted to a \( 2 \times 2 \times 2 \times 3 \) (\( [W_{eX}, W_{eY}] \) \( \times \) MT \( \times \) Impact Magnitude \( \times \) Session) ANOVA, with repeated measures on all factors.

The movement variability was similar in both directions, 6.0 and 5.6 mm for \( W_{eX} \) and \( W_{eY} \), respectively, \( F(1, 3) = 0.63, p > .05 \). Movement variability was larger when a small impact magnitude was imposed than when a large impact magnitude was imposed, 6.5 versus 5.1 mm; \( F(1, 3) = 46.98, p < .01 \), implying that subjects increased their movement consistency when they were allowed to use the impact with the target to decelerate their limb. Despite subjects' having more time to make corrections, similar results were obtained for the 500-ms movements—on average, 5.7 and 5.9 mm for the 250-ms and the 500-ms movements; \( F(1, 3) = 0.46, p > .05 \), for the main effect of MT. There was a decrease in endpoint variability with practice (from 6.7 mm on Day 1 to 5.3 mm on Day 3), but the difference was not statistically significant, \( F(2, 6) = 2.03, p > .05 \). Overall, the results suggest that subjects could increase their movement consistency by using the impact with the target to decelerate their limb.

**Discussion**

Overall, the data show that the structure of the acceleration-time functions was affected by the magnitude of the imposed impact. For example, the duration of the acceler-

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**TABLE 2**

<table>
<thead>
<tr>
<th>Movement time</th>
<th>Impact magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Large</td>
</tr>
<tr>
<td>250 ms</td>
<td>5.2</td>
</tr>
<tr>
<td>500 ms</td>
<td>8.4</td>
</tr>
</tbody>
</table>

**FIGURE 2.** Movement endpoint variability for the different conditions of impact magnitude and MT.
ation phase was slightly longer than the duration of the deceleration phase when a small impact magnitude was imposed (on average, 137 and 112 ms for the 250-ms movements), whereas the acceleration phase was more than 4 times longer than the deceleration phase when a large impact was imposed (on average, 212 and 43 ms for the 250-ms movements). Those differences resulted in the subjects' being always closer to target contact (at a given time before contact) when a small impact was imposed than when a large impact was imposed.

In the present experiment, the aiming requirements for both conditions of impact magnitude were similar (i.e., to hit the center of a 20-cm² target). Therefore, the differences observed in the structure of the acceleration-time functions cannot be attributed to differences in aiming requirements. Rather, they must be attributed to the stopping or deceleration requirements. In Fitts-like tasks, longer deceleration phases have been previously interpreted as being a reflection of the precision demands of a movement (Mackenzie, Marteniuk, Dugas, Liske, & Eickmeier, 1987; Marteniuk et al., 1987). Because the aiming and the decelerating components of the movement are confounded in Fitts-like tasks, it is possible, however, that increased precision demands (through decreasing target size) do not simply affect the aiming demands but also indirectly impose constraints on the stopping demands of the movement. In support of this suggestion, Worthingham (1987) has shown that impact forces decrease linearly with a decreased target size, implying that a decreased target size also imposes some specific deceleration demands on the movement. As such, we believe our results provide an alternative hypothesis to account for Marteniuk and colleagues' data: The shifts in the duration of the deceleration phases could be a necessary physical consequence of the implied impact constraints rather than the result of an increased or a better use of the available sensory information.

Clearly, the specific MT and deceleration requirements created a fundamentally different control problem in the present experiment than in experiments for which the deceleration phase was critical for movement accuracy and control (e.g., Beaubaton & Hay, 1986; Carlton, 1980, 1981; Meyer et al., 1988). Further, there have been numerous reports on experiments in which the deceleration phase of a movement was longer than the acceleration phase (e.g., Carlton, 1980; Zelaznik et al., 1986). It is possible that increasing the duration of the acceleration phase in the present experiment served to reduce the variability associated with the initial programmed part of the movement. Alternatively, it is also possible that, because of the specific temporal and impact requirements, the initial phase was under sensory control, whereas the terminal phase was preprogrammed. In support of this argument, Bard and colleagues (Bard & Hay, 1983; Bard, Hay, & Fleury, 1985; Bard, Paillard, Fleury, Hay, & Larue, 1990) have shown that, in tasks emphasizing directional uncertainty, the role of vision in the initial phase of the movement is as important as in the terminal phase of the movement. Thus, the actual mode of control may be task-dependent rather than stereotyped in such a way that an initial preprogrammed phase is always followed by a current control phase. Future experiments should allow us to explore this possibility in further detail.

Impulse-variability models (Meyer et al., 1982; Schmidt et al., 1979) suggest that the impulses produced by the muscles generate variability in amplitude proportional to the amount of force produced and variability in duration proportional to the duration of the movement. This impulse variability presumably leads to greater trajectory and endpoint variability when the average velocity of the movement (A/MT) is increased. Under a strict impulse-variability viewpoint, all the deceleration of a moving limb is accounted for by the muscular system. It is possible that subjects could benefit from using the impact to decelerate their limb because, when more impact is used, less of the muscular system responsible for decelerating the limb is necessary, thereby allowing the subject to save some muscular variability. This suggestion is certainly a simplification of the agonist-antagonist relation. Waters and Strick (1981), however, have shown that antagonistic activity is nearly abolished when subjects are allowed to terminate their movement by hitting a mechanical stop, as compared with agonist activity of subjects who have to decelerate precisely. In the present experiment, subjects exhibited more endpoint variability when a small impact magnitude was imposed than when a large impact magnitude was imposed, thus providing initial support for this hypothesis.

In the present experiment, an increased MT did not yield a decreased endpoint variability. Considering that subjects were instructed to be spatially as accurate as possible, it is possible that subjects traded some additional aiming accuracy for an increased variability in the third dimension of precision (i.e., impact). Because variability in this third dimension of spatial accuracy was experimentally controlled, the data did not permit evaluation of such a possibility.

Because the structure of the acceleration-time functions were so dramatically affected by the different impact-magnitude requirements, it is tempting to suggest that the results do not support a movement production mechanism that creates trajectories by a simple temporal scaling (e.g., Gentner, 1987; Marteniuk et al., 1987; Soechting, 1984). Heuer (1988) recently suggested, however, that the view that there exists a specific temporal structure for each category of movements might be too rigid; he suggested that temporal patterns differ on one or more continua and that positions on these continua are determined by parameters of the same generalized motor program. Hence, it might well be that the impact a subject can "afford" to produce in a task is a parameter that is accounted for when programming a movement. According to this hypothesis, the bell-shaped velocity profiles would be systematically modified as a function of the impact a subject can afford to make. Zelaznik, Slotta, and Rosenbaum (1989), though they rejected the rigid notion that movements are governed as units, also presented an alternative account for the nonscalability of such movements; they suggested that trajectory
formation is determined by defining the temporal location at which a subject must trigger the onset of the deceleration in order to achieve a specified movement time. In such a model, the possibility of affording a given impact to decelerate the limb would also be critical for the precise determination of deceleration onset and thus, trajectory formation.

The role of the deceleration requirements in the control of movements may also vary as a function of the specific temporal requirements. For example, for movements without specific temporal constraint in which terminal corrections are possible, an increased muscular activity may not produce an increased aiming variability, as reported in the present experiments, but rather a decreased aiming variability. Such would be the case if the muscular activity acts to correct the aiming errors. The acceleration-time functions presented in Carlton (1981) suggest such a mode of control; indeed, the subjects were completely decelerating their movement prior to hitting the target, and this deceleration phase was followed by a short reacceleration phase. Worthingham (1987) reported similar variations (possibly corrections) in pointing movements. Darling and colleagues (Darling & Cooke, 1987; Darling, Cooke, & Brown, 1989) also suggested that appropriately timed and modulated antagonists bursts are necessary for the reduction of variability in the deceleration phase of step-tracking movements.

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