The control of two-element, reciprocal aiming movements: Evidence for chunking


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Abstract

This study evaluates the chunking hypothesis in the context of two-element, reciprocal aiming movements. The chunking hypothesis assumes that movements toward small targets require a movement stop while movements toward large targets require a movement reversal. According to the chunking hypothesis, a movement reversal allows for a functional coupling or linkage between the forward and backward movement such that braking energy generated by antagonist activity in the forward movement is stored as elastic energy and re-utilized as acceleration energy in the backward movement (Guiard, 1993). An experiment is reported which examined movement kinematics of left–right reversal movements using four different target combinations; small–small, small–large, large–large, and large–small, for left and right targets, respectively. The results accommodated predictions derived from the chunking hypothesis. Several implications for motor control theory are discussed.

1. Introduction

Recently, Adam et al. (1993) reported that a discrete movement toward a single target is executed slower than the same movement when it is followed by a second movement (i.e., a reversal movement) toward a target positioned in the opposite direction. However, this two-target advantage or, more accurately, reversal advantage phenomenon only materialized for
large targets, not for small targets; small targets resulted in equivalent movement times to the first target (MT1) for both discrete and reciprocal responses.

Accounting for this difference, Adam et al. (1993) speculated that a reciprocal response toward large targets (i.e., a fast flexion–extension response) does not have to stop but rather to reverse movement direction on the first target. Specifically they argued that the control mechanisms of stopping a movement and reversing a movement are different. A discrete movement typically requires a three-burst EMG pattern of agonist–antagonist–agonist activity with the last agonist activity damping possible oscillations in order to stop and fixate the limb (or stylus) on the target (Enoka, 1988; Hallett et al., 1975; Hannaford and Stark, 1985). In a fast reversal movement, on the other hand, the last component of this three-burst activity pattern is usually absent (Enoka, 1988), possibly allowing for shorter MT1s.

For reciprocal movements toward small targets (3 mm), however, the distinction between stopping and reversing a movement might not be relevant. This is so, because small targets require that both discrete and reciprocal movements stop on the first target so that subjects can evaluate their movement’s endpoint accuracy. In other words, reciprocal aiming movements toward small targets may be thought of as two discrete movements separated by a distinct period of “standstill”. Indeed, analysis of these periods of “standstill” on the first target, also called dwell times (see Adam, 1993; Adam and Paas, 1994), revealed that they were much longer on the small target than on the large target (130 versus 15 ms, respectively).

The above line of reasoning is consistent with Guiard’s (1993) recent analysis of reciprocal or cyclic aiming movements in terms of energy constraints. Based on Hooke’s Law, Guiard (1993) argues that cyclicity offers the possibility of saving mechanical energy due to the ability of muscles to store mechanical energy in a potential, elastic form towards the end of each movement to the benefit of the next (see also Cavagna, 1977). Specifically, Guiard contends that antagonist muscle activity at the end of a movement in cyclic aiming behaviour might accomplish two goals: (1) terminate the movement; and (2) simultaneously start the next. According to Guiard, the fusion of terminal braking and re-acceleration at movement reversals saves mechanical energy. Experimentally, Guiard (1993) was indeed able to show that the degree of fusion varies as a function of movement speed; that is, fast cyclic movements show distinct fusion effects, i.e., save energy by storing and re-utilizing elastic energy, but slow, accurate
cyclic movements do not or do so to a lesser extent. In other words, as the rhythm of cyclic activity slows down, component movements become slower, and antagonist activity becomes less and less energy efficient in that its breaking activity and re-acceleration activity become temporally separate events.

This kind of analysis corroborates the notion that in certain circumstances serial ordering of movements might lead to a response organization called a chunk. A chunk is characterized by dependencies or functional linkages between its constituent components. That is, according to the chunking hypothesis reversal movements toward large targets are the result of a response organization in which the individual movements are functionally integrated; this integration involves the storage and subsequent use of elastic energy. Reciprocal movements to small targets do not show this kind of response organization because they are separated in time by a distinct period of “standstill”, possibly allowing visual feedback processes to evaluate the accuracy of the response and preparatory processes to “prepare” the next response. Thus, individual movements in a reciprocal response toward small targets can be regarded functionally independent.

In this study we investigated the chunking hypothesis by studying the kinematics of two-element, reciprocal (i.e., left-right) aiming responses. We used two target sizes: targets with diameters of 3 and 60 mm. Using these targets we constructed four target combinations (for left and right targets, respectively): small–small, small–large, large–large, and large–small.

In order to evaluate the chunking hypothesis, two kinds of analysis seem prudent. First, kinematics of the first movement should be examined in relation to the size of the second target. When the first target is small, the chunking hypothesis would predict that the size of the second target should not influence the kinematics of the first movement; this is so, because the first and second movement are temporally separated by a substantial period of dwell time, and thus functionally independent. When the first target is large, the chunking hypothesis would predict that the size of the second target should influence the kinematics of the first movement because they are functionally organized into one response chunk. In

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1 The notion of response chunk is related but not identical to the concept of response synergy (Bernstein, 1967; Kugler and Turvey, 1987; Rosenbaum, 1991; Whiting, 1984). Whereas the former refers to the integration of successive movements, the latter refers to the integration of simultaneous movements. We thank an anonymous reviewer for pointing this out.
particular it is hypothesized that movement time to the first target (MT1) is shorter when the second target is large than when the second target is small. This is so, because the second large target allows maximal exploitation of elastic energy generated during the course of terminating the first movement in order to complete the second movement as quickly as possible. This maximal generation and exploitation of elastic energy might not be an optimal strategy when the second target is small, which demands a more accurate and therefore slower movement (Adam, 1992; Fitts, 1954; Schmidt et al., 1979).

Second, kinematics of the second movement should be considered as a function of the size of the first target. Here, both for small and large second targets, the chunking hypothesis would predict that a large first target would offer the opportunity of storing elastic energy during the first movement which subsequently could be exploited to execute the reversal movement. A small first target, alternately, would not, or at least to a lesser extent, offer this opportunity because the relatively slower speeds (i.e., smaller forces) associated with movements toward small targets allow less elastic energy to be stored and re-utilized for the reversal movement; moreover, a small first target is characterized by a substantial period of "standstill" during which elastic energy might dissipate. Therefore, reversal movements departing from a large first target should exhibit shorter movement times and larger peak velocities, and should reach peak velocity sooner than reversal movements departing from a small first target.

2. Method

2.1. Subjects

Eighteen students (10 female and 8 male) of the University of Limburg participated in this study (mean age, 22.7 years; range 20 to 28). They were all right-handed and volunteered to participate.

2.2. Apparatus and tasks

A 61 × 91 cm X–Y digitizing tablet (Scriptel Corporation), mounted on a 80 cm high table, was used in conjunction with a MS-DOS AT computer to record time-X data pairs. Sampling rate was 135 Hz, and spatial accuracy of the digitizing tablet was set at 0.1 mm.
Four target sheets were constructed, each consisting of two circular targets horizontally separated by 10 cm (i.e., the distance between the centres of the two targets). The diameter of the targets was either 3 mm or 60 mm. Using these targets we constructed four target combinations: small–small, small–large, large–large, and large–small. Target sheets were placed on top of the digitizer and covered by a piece of clear glass.

2.3. Procedure

Subjects stood facing a table on which the $X-Y$ digitizing tablet was mounted. They were asked to hold a stylus in a pen-grip fashion and, following an auditory start signal, to slide the stylus smoothly and as quickly as possible from the right target to the left target and then back to the right target. It was emphasized that they had to reverse the movement within the boundaries of the left target and to stop within the boundaries of the right target. After a short period of familiarization with the different experimental conditions, subjects performed 10 test trials in each of the 4 target combinations (i.e., movement conditions). Order of movement conditions was random.

2.4. Data analysis

Movements were analyzed off-line, using a noninteractive computer program. The following dependent measures were calculated for both movement 1 and 2: distance travelled, movement time, peak velocity, acceleration time (time from initiation of a movement to that of peak velocity), deceleration time (time from peak velocity to zero velocity at the end of the movement), normalized acceleration time (percentage of movement time spent in acceleration), normalized deceleration time (percentage of movement time spent in deceleration), and variable error as a measure of movement accuracy (the within-subject standard deviation of the movement endpoints about their own mean). In addition, dwell time was calculated: the period of time the speed of the stylus was zero during the reversal of the movement on the first target. Note that dwell time was not part of movement time. These dependent variables were formed from the average of the subject’s 10 test trials.

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2 Since subjects travelled, on average, the same distance in all conditions (see Table 1) variable error rather than absolute error was used as an index of accuracy.
2.5. Statistical analysis

Within-subject (i.e., repeated measures) one-factor analyses of variance (ANOVAs) were conducted on the several movement characteristics of movements 1 and 2 as a function of the four different movement conditions (i.e., small-small, small-large, large-large, and large-small). In determining significance levels, the Geisser-Greenhouse correction (Keppel, 1982) was used to control for violations of assumptions of homogeneity of variance and covariance. Post-hoc analyses were carried out by means of Tukey's honestly significant difference procedure: an alpha level of 0.05 was employed to determine statistical significance.

3. Results and discussion

In order to ascertain that movements to small and large targets were not different in terms of distance travelled, separate ANOVAs were carried out on the distance data for movements 1 and 2 as a function of the four movement conditions. These ANOVAs yielded no significant effects (see Table 1) indicating that movement 1 and movement 2 travelled comparable distances irrespective of target size (mean distance travelled was 99.3 and 98.1 mm, for movement 1 and 2, respectively).

Overall, variable error was considerably larger on the large targets than on the small targets (8 versus 2 mm, respectively), but there were no significant differences among the small targets nor among the large targets.

Table 1
Mean values of different movement characteristics as a function of the four target combinations

<table>
<thead>
<tr>
<th>Target combinations (left–right)</th>
<th>Movement characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MT1 (ms)</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>small-small</td>
<td>618</td>
</tr>
<tr>
<td>small-large</td>
<td>581</td>
</tr>
<tr>
<td>large-large</td>
<td>231</td>
</tr>
<tr>
<td>large-small</td>
<td>309</td>
</tr>
<tr>
<td>F(3,51)</td>
<td>131.5^a</td>
</tr>
</tbody>
</table>

Note: MT = movement time; PV = peak velocity; NA = normalized acceleration time; DIS = distance; DT = dwell time; VE = variable error; 1 = first movement (i.e., to left target), 2 = second movement (i.e., to right target).

^a p < 0.001; ^b non significant (p > 0.9).
in the different movement conditions (see Table 1). These outcomes suggest that subjects performed in accordance with the accuracy constraints imposed by the size of the targets.

The mean values of the different movement characteristics as a function of the first and second movement in all four target combinations are presented in Table 1, together with corresponding $F$- and $p$-values.

Fig. 1 depicts mean movement time as a function of the first and second movement in all four target combinations.

3.1. Movement to first, small target

Consistent with the chunking hypothesis, all kinematic variables (including dwell time) of the first movement toward the small target were not significantly influenced by the size of the second target. In other words, irrespective of whether the reversal movement was toward a small or large target, the kinematics of movements made toward the first, small target were not reliably different. This suggests that when the first target is small (i.e., 3 mm), the two movements comprising a two-element reciprocal response are functionally independent. This independence is consistent with the finding that the period of “standstill” between the forward and backward movement on the first target (i.e., dwell time) was on average
only 10 ms for large targets but a striking 169 ms for small targets. The functional significance of these rather large dwell times on small targets could in the present two-element reversal response be related to (1) visual feedback processes concerned with assessing the accuracy of the first movement’s endpoint, and (2) preparation of the second, backward movement (Adam, 1992). Thus, two reciprocal movements toward a pair of small targets may be thought of as two separate, independent movements each having its own, independent preparatory and control processes.

3.2. Movement to first, large target

In contrast, the kinematics of the first movement toward the large target were significantly affected by the size of the second target. That is, when the second target was large, movements toward the first, large target showed shorter movement times and larger peak velocities than when the second target was small. This indicates that the forward and backward movement were prepared in advance together, that is, were organized into a response chunk before the start of the two-element response.

3.3. Movement to second, small target

The second, i.e., reversal, movement toward a small target was 120 ms faster when it followed a first movement made toward a large target than when it followed a first movement made toward a small target; correspondingly, peak velocities were substantially higher and reached sooner. Clearly, this too suggests a strong functional coupling between the components of a two-element, reciprocal aiming response.

3.4. Movement to second, large target

The pattern of results for the second movement toward a large target was similar to that toward a small target. That is, the second movement toward a large target was 102 ms faster when it followed a first movement made toward a large target than when it followed a first movement made toward a small target; also, peak velocities were substantially higher and reached sooner. Again, these results provide evidence in support of the chunking notion.
3.5. Reversal advantage

The chunking hypothesis easily explains why the reversal advantage only materializes for large targets and not for small targets. Reversal movements toward small targets are characterized by distinct periods of dwell time on the first target, thereby temporally and functionally forcing apart the forward and backward movement. Reversal movements toward large targets, in contrast, show much smaller dwell times, thereby allowing the backward and forward movement to fuse into a combined response, that is, a chunk. The results of the present study strongly support this distinction between "stopping" and "reversing" a movement, as mean dwell time on the small target considerably outlasted that on the large target (169 versus 10 ms, respectively).

This account is corroborated by emg data reported by Kasai and Seki (1992), who demonstrated that the duration of the initial agonist burst was longer, and emg onset of antagonist activity occurred later in time, for the first movement in a reciprocal response compared to that of an uni-directional, discrete response.

In sum, according to the chunking hypothesis the reversal advantage results from a response organization in which the first movement in a reciprocal response accelerates longer and reaches larger peak velocities (Adam et al., 1993) because it does not have to stop on the first target (as the single aiming, discrete response has to do) but rather to reverse movement direction.

3.6. Relevance for motor control

The implications of this study for motor control theory are threefold. First, the reversal advantage phenomenon and its "chunking" interpretation in terms of storing and re-utilizing potential, elastic energy across movement reversals, is consistent with the view that continuous, cyclical movements, rather than discrete movements, constitute the basic units of motor action (Bernstein, 1967; Guiard, 1993). That is, whereas a continuous movement is more or less conservative in that mechanical energy can be stored across reversals, a single discrete movement is dissipative in that it implies waste of energy (Guiard, 1993). Consistent with the notion that cyclical movements are the fundamental entities of motor behavior is the fact that the reversal advantage phenomenon is a strong and easy to
demonstrate phenomenon, requiring in this study only 10 trials per condition to show up.

Second, the reversal advantage phenomenon belongs to a general class of phenomena called context effects: movements embedded in a sequence are not independent of each other but may mutually influence each other. Studies of handwriting, for instance, have shown that the shape and timing of a letter depends on what letter precedes it and on what letter follows it (Rosenbaum, 1991). Context effects also have been described in the study of typewriting (Terzuolo and Viviani, 1980).

Third, the reversal advantage is a laboratory phenomenon that has everyday-life equivalents. Sportsmen engaged in throwing and hitting activities, for instance, exploit the reversal advantage phenomenon to improve performance by reducing the energy and control costs (Guiard, 1993). In addition, more mundane everyday-life motor activities like knitting, hammering, handwriting, and typing also seem to be cyclically organized and may likewise benefit from muscles’ capability of storing potential, elastic energy across movement reversals (Guiard, 1993).

4. Conclusion

In the present article we investigated the chunking hypothesis and generally found its predictions supported. Essentially, the chunking hypothesis postulates that depending on the task constraints (i.e., size of the targets) the forward and backward movement of a reciprocal aiming response might be functionally related. Specifically, when the forward movement is toward a large target, its braking energy generated during the deceleration phase is stored in an elastic form and exploited in the production of the reversal movement (Guiard, 1993). When the forward movement is towards a small target, this functional linkage between the forward and backward movement in terms of storing and re-utilizing elastic energy is absent. This is so because a two-element reciprocal response toward small targets is essentially a serial concatenation of two separate, independent movements, each with its own preparatory and control processes. In order to establish the generality of the chunking notion, future research should investigate the possible mediating influence of other task constraints as, for instance, movement amplitude and amount of practice.
References


