Kinematic adaptation to sudden changes in visual task constraints during reciprocal aiming

Laure Fernandez a,c, William H. Warren b, Reinoud J. Bootsma a,*

a Movement and Perception Laboratory, University of the Mediterranean, Marseille, France
b Department of Cognitive and Linguistic Sciences, Brown University, Providence, RI, USA
c Department of Neuromotor Physiology, Fondazione Santa Lucia, Rome, Italy

Available online 21 July 2006

Abstract

In a series of three experiments the visual modulation of movement during a reciprocal aiming task was examined when participants were confronted with sudden changes in visually specified task constraints. Amplitude and precision constraints were manipulated independently in Experiments 1 and 2, respectively, while their simultaneous effects were analyzed in Experiment 3. Analysis of the evolution of kinematic characteristics following a sudden change in task constraints revealed two different times scales of adaptation: a rapid adjustment occurring during the deceleration phase of the first movement following change and a more gradual adaptation, affecting the kinematic pattern as a whole, occurring over the next few movements. Overall, the results indicate that visual information with respect to the adequacy of the unfolding movement is continuously monitored, even under the least constraining conditions, and serves to modulate the pattern of movement to (a) comply with the (new) task constraints and (b) optimally tailor the pattern of movement to the situation at hand. We interpret these findings in the framework of a dynamical perspective on movement organization, with information modulating the parameters of an otherwise invariant underlying dynamical structure.

© 2006 Elsevier B.V. All rights reserved.

PsycINFO classification: 2330

Keywords: Reciprocal aiming; Motor control; Visual information; Task constraints; Dynamics; Aiming movements; Vision

* Corresponding author. Address: UMR Mouvement et Perception, University of the Mediterranean, 163 avenue de Luminy, 13288 Marseille cedex 09, France. Tel.: +33 4 91 17 22 55; fax: +33 4 91 17 22 52.
E-mail address: reinoud.bootsma@univmed.fr (R.J. Bootsma).

0167-9457/S - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.humov.2006.05.001
1. Introduction

How might visual information influence the dynamics of ongoing movement? In the present article, we investigate this question in the context of a reciprocal aiming task, yielding a continuous oscillatory movement between two visual targets. Recent research has demonstrated that visual information can affect not only movement trajectories but also the underlying dynamic organization of movement during reciprocal aiming (Bootsma, Bouard, Fernandez, & Mottet, 2002; Fernandez & Bootsma, 2002; Mottet, Guiard, Ferrand, & Bootsma, 2001). Here we examine the role of information through sudden changes in visual task conditions and infer their effects on movement dynamics.

Theoretically, visual information might modulate the dynamics of a system on at least three levels (Saltzman & Munhall, 1992; Warren, 2006). First, it could directly affect the state of the system, altering the current limb position or velocity but leaving the basic form of the oscillatory trajectory intact. Second, information might influence the parameters of the system, altering the form of the trajectory but leaving the underlying dynamic structure invariant. Such a change could occur on a fast time scale, via discrete resetting of parameter values, or on a slower time scale, via more gradual parameter dynamics. Third, information might invoke a reorganization of the dynamical structure itself, with qualitative consequences for the movement pattern. In the present experiments we probe the modulatory effects of visual information by abruptly changing the visual task conditions and measuring the time course of adaptation in movement kinematics.

Aiming tasks have been widely used to investigate the control processes implied in goal-directed behavior. The seminal work of Fitts (1954) (Fitts & Peterson, 1964) gave birth to a powerful experimental paradigm, elegantly capturing the essence of goal-directedness: aiming for a goal requires dealing with the distance \( D \) separating the desired and the current positions, in the light of the allowable error defined by the extent (or width \( W \)) of the target to be attained. Thus, Fitts’ paradigm allows a precise control of task difficulty, operationalized by an index of difficulty with \( ID = \log_2(2D/W) \). The distance to be covered \( D \), defined with respect to the target center, constitutes a constraint on movement amplitude, while the width \( W \) of the target to be attained constitutes a constraint on precision. When task difficulty is increased, the time necessary to perform an aiming movement increases. This systematic relation has come to be known as Fitts’ law and has proven to be a powerful tool in evaluating perceptuo-motor capabilities and human–computer interfaces (e.g., Soukoreff & MacKenzie, 2004).

However, not only the time required to complete an aiming movement varies as a function of task difficulty. The kinematic pattern of the movement also changes. For discrete movements, executed at low levels of difficulty, the velocity profile is symmetrically bell-shaped, with acceleration and deceleration phases of equal duration. As task difficulty increases, the velocity profile gradually loses its symmetrical character (Beggs & Howarth, 1970; Langolf, Chaffin, & Foulke, 1976; MacKenzie, Marteniuk, Dugas, Liske, & Eickmeier, 1987; Soechting, 1984). The increase in movement time provoked by an increase in task difficulty results primarily from an increase in the duration of the deceleration phase. During this phase, adjustments of the ongoing movement (i.e., discontinuities in the velocity profile) can be observed, presumably based on visual feedback.

---

1 Although robust in the grand majority of settings, the monotonic relation between ID and MT is not a law of nature, as violations have been reported (e.g., Kelso, Southard, & Goodman, 1979).
In order to better understand the influence of visual information on the pattern of movement, experimental protocols with a sudden change in task requirements have been used. Elliott and collaborators (Elliott, Binsted, & Heath, 1999; Heath, Hodges, Chua, & Elliott, 1998) reported a series of experiments using a discrete aiming task in which the position or the size of a target was abruptly changed at the moment of onset of the movement. The results indicated that participants were able to adapt their movement to the new task constraints by modulating the kinematics of the second phase of movement. Whereas the duration of the acceleration phase and the peak velocity reached were determined by the characteristics of the initial target (i.e., before change), the duration of the deceleration phase and hence the overall movement time were functionally related to the characteristics of the new target (i.e., after change). Interpreted within the framework of the two-component model of movement (Elliott, Helsen, & Chua, 2001; Woodworth, 1899), the acceleration phase would thus be an initial ballistic phase, prepared in advance, driving the effector towards the target. During the deceleration phase, the movement would be under (visual) feedback-based control – therefore referred to as the current control phase – allowing adaptation of the movement to compensate for the errors accumulated during the first phase or to integrate changing task requirements (Carlton, 1981, 1992; Chua & Elliott, 1993; Cullen et al., 2001; Khan & Franks, 2000).

Fitts (1954) initially proposed a reciprocal task requiring continuous to-and-fro movements between two targets. However, the great majority of studies adopting his paradigm have used the discrete version of the aiming task introduced by Fitts and Peterson (1964) 10 years later, in part due to the fact that for discrete movements the beginning and the end of the movement are clearly defined. Thus, in a discrete aiming task one is sure that the processes operating during movement execution are related to the ongoing action. Yet discrete movements are not well suited to study longer-term adaptation to changing task constraints over several movements. In the present series of experiments we therefore examined adaptation to sudden changes in task requirements during a reciprocal aiming task in order to probe the time scale(s) of movement organization. Because earlier studies demonstrated that participants tailor their movement patterns to the task requirements at hand (Mottet & Bootsma, 1999; Mottet et al., 2001), analyzing kinematic characteristics of the sequence of movements following a sudden change in target position, target size, or both allowed us to investigate the way in which the movement pattern changes from one form to the other.

In a reciprocal aiming task (Fitts, 1954) participants perform back and forth movements between two targets as fast and as accurately as possible. Guiard (1993) pointed out that the movement sequence observed in reciprocal aiming cannot be reduced to a simple concatenation of discrete aiming movements. The underlying reason is to be found in the nature of the discrete task, with its clearly defined onset and end. In kinematic terms, a discrete movement is defined by the fact that velocity and acceleration are both equal to zero at the beginning and at the end of movement. In a reciprocal aiming task, the constraint on acceleration is dropped: while the point at which movement changes direction is defined by the point at which velocity reaches zero, acceleration is free to vary.

For reciprocal aiming at low levels of difficulty, the movement produced is essentially continuous. The deceleration phase of one movement, which brings the velocity to zero at the target, is merged with the acceleration phase of the next movement (Guiard, 1993).
Thus, the movement produced is a harmonic oscillation, with position varying quasi-sinusoidally over time (see Fig. 1, left panels, for an illustration of this kind of movement). Increasing the difficulty of the task, for example by using smaller targets, leads to a progressive disappearance of the movement’s harmonic character (Mottet & Bootsma, 1999). The deceleration and re-acceleration phases become more and more distinct. When the two phases are totally separate, such that deceleration becomes zero before re-acceleration begins, the back and forth motion between targets becomes a sequence of discrete movements, with mechanical energy being fully dissipated at the end of each movement (see Fig. 1, right panels, for a movement pattern of this type).

Mottet and Bootsma (1999) developed a dynamical model that captures this continuum of kinematic patterns (from continuous to discrete) through variations in the model’s

![Fig. 1. An exemplary time series of kinematic data drawn from Experiment 2, for a trial with a sudden decrease in target size. Panel A shows the evolution of cursor position over time (with the location and size of the targets indicated by the gray bars). Panels B–D show details of position, velocity, and acceleration for the movement before change ($D = 20\,\text{cm}$, $W = 2.5\,\text{cm}$, ID = 4). With the position signal added to panels C and D (in gray), the harmonic character of the movement pattern is to be seen in the anti-phase co-variation of the acceleration and position signals. Panels E–G show details of position, velocity, and acceleration for the movement well after change ($D = 20\,\text{cm}$, $W = 0.625\,\text{cm}$, ID = 6). The deceleration to bring the cursor to zero velocity in the target area is now clearly dissociated from the subsequent acceleration to move the cursor towards the next target.]
parameters, while maintaining an invariant underlying dynamical structure, expressed as an equation of motion. The terms included in the model were linear and non-linear conservative and dissipative terms. The conservative (position-related) terms determine the stiffness characteristics of the system. The dissipative (velocity-related) terms determine the damping and escapement characteristics of the system. Fitting the model to data obtained under 25 different conditions of distance and target size, Mottet and Bootsma (1999) observed an increase in the contribution of the non-linear terms with increasing task difficulty. They concluded that the systematic changes observed in the kinematic patterns of movement in the reciprocal version of Fitts’ aiming task could be understood as resulting from changes in the parameters of an otherwise invariant underlying dynamical structure. In the terms of Saltzman and Munhall (1992), the level of graph dynamics (i.e., the dynamical structure) underlying the task remained unchanged for the different amplitude and precision conditions. Parameter dynamics are at work in the adaptation to different levels of task difficulty, while the unfolding of the movement for a given level of task difficulty is governed by state dynamics.

Fernandez and Bootsma (2002) further explored the origins of these systematic changes in kinematics. In this study, participants displaced a hand-held stylus over a graphics tablet so as to move a cursor between two targets presented on a screen. The reciprocal aiming task was performed under conditions differing with respect to the mapping between the physical space in which the stylus moved (effector space) and the visual space in which the cursor moved (task space). In one condition, this mapping (i.e., the gain function linking stylus and cursor) was linear. In a second condition, the mapping was non-linear, with the gain function chosen such that, for a harmonic movement of the stylus in effector space, the motion of the visual cursor in task space mimicked the non-harmonic pattern typically observed at higher levels of task difficulty. With this non-linear gain function participants actually produced more harmonic movement patterns in effector space. The authors concluded that movement was organized in task space rather than in effector or motor space, in line with the theoretical perspective of Saltzman and Kelso (1987). These results demonstrate the role of visual information (informing about the state of affairs in task space) in the organization of movement in a reciprocal aiming task.

While previous work in reciprocal aiming has thus concentrated on differences between conditions, the present study addressed the visual modulation of reciprocal aiming movements by sudden changes in task requirements. We report a series of three experiments in which the visually specified constraints on movement amplitude and precision were manipulated during ongoing action. The goal of this experimental series was twofold. In the first place, we sought to identify the time scale(s) of parameter dynamics. To this end we analyzed the temporal characteristics of the transition from one kinematic pattern to another, evoked by a sudden change in task constraints. In the second place, we sought to analyze how the form of movement was adapted to a sudden change in task requirements. In other words, we examined the nature of the evolution of kinematic characteristics over a series of aiming movements following the change in task requirements.

In Experiment 1 we manipulated the required amplitude of movement, while in Experiment 2 the size of the target was suddenly changed. Since both of these manipulations led to changes in the difficulty associated with the task, as captured by the ID, Experiment 3 examined the adaptation to a sudden change in both distance and target size, chosen so as
to maintain the overall difficulty of the task at the same ID level. By comparing our results to those obtained by Heath et al. (1998), the question of whether the constraints on amplitude and precision affect the organization of movement in a reciprocal aiming task in the same way as in a discrete aiming task can thus be addressed. As we hypothesize that the flow of information in task space plays a primary role in structuring the kinematics of movement (Fernandez & Bootsma, 2002, 2004; Mottet et al., 2001), we expect to find that movement is under continuous informational control.

2. General methods

2.1. Participants

With 10 participants per experiment, the experimental series included a total of 30 adults ranging in age from 19 to 27 years. All had normal or corrected-to-normal vision. Participants gave their informed consent prior to inclusion in the study, which was approved by the local ethics committee.

2.2. Apparatus

Participants sat comfortably at a table, facing a computer screen (Dell M991, 1024 × 768 pixels) with a graphics tablet (WACOM UltraPad A3) placed horizontally on the table in front of them. A Dell PC connected the graphics tablet with the screen. Left–right motion of a hand-held, non-marking stylus on the graphics tablet was linked to the left–right displacement of a cursor on the computer screen via a dedicated software program developed in the laboratory. The gain between the displacement of the stylus on the graphics tablet and the displacement of the cursor on the computer screen was unitary (1 cm on the graphics tablet corresponded to 1 cm on the computer screen). Because previous research demonstrated that the motion component along the up–down direction on the graphics tablet was small and unrelated to the characteristics of motion along the primary (left–right) direction, only the latter was taken into account for the cursor who thus moved along a straight line in task space. The position of the stylus on the graphics tablet was sampled at a frequency of 100 Hz.

2.3. Procedure

Participants performed a reciprocal aiming task, consisting of moving the cursor (a 35-cm red vertical line segment) back and forth between two vertically elongated (35 cm) white targets depicted on the screen against a black background. The instructions were to perform the task as fast and as accurately as possible, with errors defined as movement reversals occurring outside the target area. A trial consisted of 100 consecutive aiming movements from one target to the other. After the first 60 movements, a change could intervene in between-target distance \( D \) (Experiment 1), in target size \( W \) (Experiment 2) or in both \( D \) and \( W \) simultaneously (Experiment 3). The change always occurred at the moment the cursor left the target area. Following the change, 40 aiming movements were performed under the new task requirements. Experimental conditions in which a change occurred were randomly intermingled with control trials in which no change occurred. Participants were not informed whether
an upcoming trial would be an experimental or a control trial. Under all conditions, the first 60 aiming movements had to be performed with fewer than 5% errors. If this criterion was not met, the trial was re-run. Task instructions stipulated that participants should try to be as fast and as accurate as possible even if a change occurred. However, as we did not know a priori how long adaptation to the change would take, aiming errors produced after the change were not taken into account.

2.4. Data analysis

For each trial, data were segmented according to the following logic. The first 20 aiming movements served to stabilize the kinematic pattern and were not analyzed. The following 40 aiming movements (21–60) constituted the “before” segment. The 40 aiming movements following the change in task requirements were subdivided into two sets. The first set consisted of the first 10 aiming movements immediately following the change (61–70 constituting A1–A10) and served to characterize the transition from one pattern to the other. The second set consisted of the last 30 aiming movements (71–100) and constituted the “after” segment.

The position time series were filtered with a dual-pass, second-order Butterworth filter, with a cut-off frequency of 5 Hz. Velocity and acceleration were subsequently derived using a 3-point central difference technique.

Kinematic characteristics of individual aiming movements were obtained by identifying movement reversals (position extremes). For each trial movement time was defined as the (mean) duration between movement reversals, movement amplitude as the (mean) spatial extent, and peak velocity as the (mean) maximum of velocity reached. The duration of the acceleration phase was defined as the time from movement reversal to peak velocity and the duration of the deceleration phase as the time from peak velocity to the next movement reversal.

The global form of movement under the control conditions was characterized by average velocity profiles. These profiles were obtained by averaging, first over repeated aiming movements and then over participants, the instantaneous velocities at constant phases of the movement (using steps of 5% of movement time). Separate velocity profiles were derived for the right–left and left–right movements.

Three series of statistical analyses, using repeated measures analysis of variance (ANOVAs), were performed. First, we analyzed the control conditions in order to characterize the kinematic patterns observed with various target distances and sizes. Second, we compared the “before” (21–60) and “after” (71–100) segments of the experimental conditions to the corresponding control conditions, to determine whether behavior had stabilized before and after the change, similar to baseline performance. Finally, the first 10 aiming movements (A1–A10) after the change were compared to the before segment (21–60) and the after segment (71–100), to examine the adaptation of kinematic parameters in experimental conditions. In this analysis, the ANOVA included a repeated factor of time (12 levels: before, A1, A2,…, A9, A10, after), followed by extensive post hoc analyses (Newman–Keuls) to compare each of the “transient” values (A1–A10) to the mean “before” and “after” values. To simplify presentation of these many comparisons, we report significant effects with a cut-off of $p < .05$, and indicate significant differences between transient values and the before segment by using filled symbols (as opposed to unfilled symbols) in the figures representing kinematic variables in A1–A10.
3. Experiment 1: Kinematic adaptation to a sudden change in distance

The purpose of the first experiment was to evaluate adaptation to a sudden change in the required amplitude of movement. Experimental trials began with a standard inter-target distance, which then changed by 25% to a greater or smaller distance.

3.1. Method

Each experimental trial started with an inter-target distance $D$ of 20 cm (center to center), with target size $W$ (for both targets) equal to 2.5, 1.25 or 0.625 cm. These combinations of $D$ and $W$ gave rise to tasks with indices of difficulty $[ID = \log_2(2D/W)]$ of 4, 5 or 6. After the first 60 movements, $D$ was changed by 25% at the moment the cursor left the target area. This change in distance between target centers was effected by displacing both targets in opposite directions at the same moment, thus maintaining the midpoint of the reciprocal aiming task at the same location.

Due to the simultaneous displacement of the two targets, the change in required amplitude of movement actually proceeded in two steps. For the first aiming movement following target displacement (A1), $D$ was 12.5% greater or smaller than before. Because the other target was displaced at the same time, the required amplitude for the second movement (A2) again increased or decreased by 12.5%. Thus, the change in required amplitude for A1 was available at the onset of the A1-movement, whereas the change for A2 was available well before the onset of the second movement (i.e., during the execution of A1). For subsequent aiming movements (A3, A4, etc.), the required amplitude remained constant.

From the initial 20 cm, $D$ either increased to 25 cm (22.5 cm for A1) or decreased to 15 cm (17.5 cm for A1). When crossed with three target sizes, this yielded six experimental conditions. They were randomly interspersed with nine control conditions, which were formed by crossing the three distances ($D = 15, 20, 25$ cm) with the three target sizes ($W = 2.5, 1.25, 0.625$ cm). The control conditions thus corresponded to nine different IDs, ranging from 3.58 to 6.32. Participants performed one trial in each of the nine control conditions and six experimental conditions during a single session that lasted about 1 h.

3.2. Results

3.2.1. Control conditions

Linear regression of movement time onto ID corroborated, once again, the close relation between movement time and ID (Fitts, 1954; Fitts & Peterson, 1964) with ID explaining 99.2% of the variance in movement time, averaged over participants ($MT = -0.43 + 0.25$ ID).

Amplitude. For each condition, movement amplitude closely corresponded to the distance between target centers. Indeed, a repeated measures ANOVA revealed a significant main effect of distance, $F(2,18) = 36008.73$, $p < .001$, with average amplitudes of 15.03, 20.00, and 24.97 cm for the 15, 20 and 25 cm distance conditions, respectively. Target size also affected movement amplitude, $F(2,18) = 5.85$, $p < .05$, with a slightly smaller amplitude for the larger targets (19.97, 20.04, 20.09 cm for the 2.5, 1.25 and 0.625 cm targets, respectively). The interaction between distance and target size did not reach significance, $F(4,36) = 1.11$, $p = .37$. 

Peak velocity and movement time. Larger distances were traversed with higher peak velocities, $F(2, 18) = 67.06, p < .001$ (see velocity profiles in Fig. 2). However, the increase in (peak) velocity was not sufficient to attain isochrony, for greater distances were associated with longer movement times, $F(2, 18) = 91.34, p < .001$. The duration of the acceleration phase increased with distance (293, 326, 342 ms for the 15, 20 and 25 cm distances, respectively), as did the duration of the deceleration phase, $F(2, 18) = 82.37, p < .001$ (448, 538, and 584 ms, respectively). On average, the latter phase occupied 60.5%, 62.3% and 63.1% of the total movement time for the 15, 20 and 25 cm distances, respectively.

A decrease in target size was accompanied by a decrease in peak velocity, $F(2, 18) = 4.72, p < .05$ (see Fig. 2). This lowering of velocity gave rise to longer movement times, $F(2, 18) = 252.26, p < .001$. While the velocity profile remained symmetric under the largest target size condition ($W = 2.5$ cm), asymmetries arose for the smaller targets. These asymmetries resulted from a moderate increase in the duration of the acceleration phase.
$F(2,18)=14.84, p<.001$, and a considerably larger increase in the duration of the deceleration phase, $F(2,18)=249.77, p<.001$ (see Fig. 2). On average, the latter occupied 52.6%, 60.5%, and 68.2% of the total movement time for the 2.5, 1.25 and 0.625 cm targets, respectively.

No interactions of distance and target size were observed for any of the kinematic variables.

3.2.2. Experimental conditions

“Before” and “after” segments. Analysis of the kinematic characteristics before and after target displacement revealed that, once stabilized, the patterns of movement were adapted to the task requirements. Before change, the kinematic characteristics were very similar to (and could not statistically be distinguished from) those observed in the control conditions for 20-cm movements directed towards target sizes of 2.5, 1.25, or 0.625 cm. Following an increase in distance (from 20 to 25 cm), the kinematic characteristics of the after segment were very similar to those observed under the control conditions for 25-cm movements, with no statistical differences. A decrease in distance (from 20 to 15 cm) gave rise to kinematic characteristics that did not fully attain the characteristics of the corresponding control conditions: the duration of the deceleration phase was slightly greater in the experimental conditions (264, 474, and 679 ms) than the control conditions (263, 423, 656, for the 2.5, 1.25 and 0.625 cm targets, respectively), $F(1,9)=5.94, p<.05$, and overall movement time remained slightly longer in the experimental conditions (513, 787, and 1024 ms) than in the control conditions (513, 734, 975 ms), $F(1,9)=8.16, p<.05$. Notwithstanding these small differences, the kinematics exhibited considerable change following target displacement, so we now turn our attention to the adaptation phase.

Increase in distance. Target displacement occurred when participants left the last-attained target to begin the 61st aiming movement (A1). Thus, this movement was already underway when the change occurred. For A1, the amplitude of movement increased, reaching 22.04 cm on average. Although not perfectly matching the center-to-center distance $D$ of 22.5 cm, on average participants managed to extend the movement to reach the inside border of the target, increasing amplitude somewhat more under the smaller target size conditions (see Fig. 3, top row; gray lines indicate required amplitude). Peak velocity remained unaffected during A1 (Fig. 3, middle row), and thus this amplitude increase was achieved by lengthening the duration of the deceleration phase, thereby increasing the overall movement time (Fig. 3, bottom row).

For A2, the required amplitude was again greater, reaching 25 cm center-to-center. However, these new task requirements were now specified well before the onset of the movement, since the position of both targets had changed at the onset of A1. The observed movement amplitude increased for A2, reaching 24.21 cm on average. Again, participants increased the extent of their movement to reach the inside border of the target (Fig. 3, top row). However, this adaptation was now accomplished by an increase in peak velocity (Fig. 3, middle row), whereas the duration of the deceleration phase and overall movement time returned to baseline values, with the latter being attained after 2 or 3 aiming movements (Fig. 3, bottom row).

Decrease in distance. A decrease in required amplitude to 17.5 cm also gave rise to an adaptation in the extent of movement for A1, reaching 18.38 cm on average. The adaptation in movement amplitude was larger in the conditions with the smaller targets (see
Fig. 4, top row). However, there was neither a significant corresponding change in peak velocity (see Fig. 4, middle row), nor in movement time or its components (see Fig. 4, bottom row). The second movement A2 had a mean amplitude of 16.39 cm and was marked by a decrease in peak velocity (Fig. 4, middle row). Finally, Fig. 4 (bottom row) indicates that while the movement time for A2 increased significantly in the large target condition, it tended to decrease in the other two conditions. During the subsequent aiming movements, there were no further significant changes in kinematic characteristics.

The results of Experiment 1 reveal that participants respond to a sudden change in target distance by adjusting movement amplitude in the appropriate direction on the first aiming movement. When target distance increased, they adapted by increasing the duration of the deceleration phase on A1 and increasing the peak velocity on A2. When target distance decreased, the peak velocity was also adapted on A2. These initial results suggest that visual information about task conditions is continuously monitored and can modulate a reciprocal aiming movement within the first half-cycle.
The purpose of the second experiment was to investigate adaptation to a sudden change in target size, which determines the required precision of movement. The increase in target size lowered the ID by one or two units, and the decrease in target size raised the ID by one or two units.

4.1. Method

The distance between target centers was held constant at 20 cm, with target sizes of 2.5, 1.25, and 0.625 cm. In the control conditions ID was thus equal to 4, 5 or 6. There were six experimental conditions: the size of both targets increased simultaneously after the 60th aiming movement from 0.625 to 1.25 cm (ID 6 to 5), from 0.625 to 2.5 cm (ID 6 to 4), or...
from 1.25 to 2.5 cm (ID 5 to 4), or decreased from 2.5 to 1.25 cm (ID 4 to 5), from 2.5 to 0.625 (ID 4 to 6), or from 1.25 to 0.625 cm (ID 5 to 6).

4.2. Results

4.2.1. Control conditions

Amplitude. The amplitude of movement (20.07 cm on average) was not significantly affected by target size, $F(2, 18) = 1.71, p = .21$.

Peak velocity and movement time. As can be seen from the velocity profiles in Fig. 5, peak velocity decreased with decreasing target size, $F(2, 18) = 4.75, p < .05$. Hence, movement time increased with decreasing target size consistent with Fitts’ law, with MTs of 468, 697 and 859 ms, on average, for the 2.5, 1.25 and 0.625 cm targets, respectively, $F(2, 18) = 88.17, p < .001$. The duration of the acceleration phase (230 ms on average) was not significantly affected by target size, $F(2, 18) = 1.42, p = .27$, and hence the increase in movement time was due to an increase in the duration of the deceleration phase, $F(2, 18) = 122.86, p < .001$. Consequently, with decreasing target size velocity profiles lost their symmetrical character (see Fig. 5), such that the deceleration phase occupied on average 52.6%, 66.5%, and 72.1% of the total movement time for the 2.5, 1.25 and 0.625 cm targets, respectively.

4.2.2. Experimental conditions

“Before” and “after” segments. Analysis of the kinematic characteristics of the experimental trials during the “before” and “after” segments revealed that the patterns of movement were tailored to the task requirements. The kinematic characteristics in both the before and after change segments were close to those observed under the corresponding control conditions. No statistically significant differences were observed.

Size increase. When target size suddenly increased, reducing the task difficulty, no significant changes occurred during A1. Movement time decreased during A2, due to a shortening of the deceleration phase, and continued to gradually approach baseline values during the
subsequent aiming movements (Fig. 6, bottom row). Due to a large between-participant variability, peak velocity did not reveal significant changes. Inspection of Fig. 6 (middle rows) nevertheless suggested a gradual increase after 4 or 5 aiming movements.

**Size decrease.** When target size suddenly decreased, raising task difficulty, A1 was characterized by an increase in movement time (significant only for the greatest change, from 2.5 to 0.625 cm). As neither the peak velocity (Fig. 7 middle row) nor the duration of the acceleration phase changed during A1, this increase in movement time can be attributed to a lengthening of the deceleration phase (Fig. 7, bottom row, also significant for the change from 2.5 to 0.625). In A2, peak velocity decreased to a level below the corresponding control value, then subsequently returned to baseline. A similar pattern occurred for the change from large to medium target size (2.5 to 1.25 cm, Fig. 7 bottom row right), with an initial overshoot of the baseline followed by a gradual return. The pattern was less clear for
changes to the smallest target (Fig. 7, bottom row), with movement time reaching baseline values on A2, due to a lengthening of the deceleration phase.

Experiment 2 thus demonstrated that participants respond to a sudden decrease from the largest to the smallest target by lengthening the deceleration phase, and hence increasing the movement time, on the first aiming movement A1. Peak velocity is then adapted on A2, and gradually moves to baseline values on subsequent movements. In contrast, when target size increases there is no immediate adjustment, presumably because there is no change in task demands, and temporal variables gradually relax to the new baseline values. This indicates that the rapid adjustments in A1 observed in other conditions are not due to a reflexive “startle response” to a change in the display, but are task-specific adaptations. The results confirm that visual information is continuously monitored and can rapidly modulate reciprocal aiming movements.

Fig. 7. Evolution of kinematic characteristics over the 10 aiming movements following a sudden decrease in target size (left, middle, and right rows). The first and the last value represent the average of the parameter for the “before” segment (represented in the figure by the letter B) and “after” segment (represented in the figure by the letter A), respectively. Upper panels represent amplitude of movement, middle panels represent peak velocity and lower panels represent temporal variables (movement time in black and duration of the deceleration phase in gray). The error bars represent the standard error of the mean (SEM). Filled symbols indicate that values are significantly (black: \( p < .05 \), gray: \( p < .1 \)) different from the “before” value.
5. Experiment 3: Kinematic adaptation to a sudden change in distance and target size with a constant task difficulty

In the first two experiments, separate manipulation of target distance or target size yielded concomitant changes in task difficulty (ID). The purpose of Experiment 3 was to test whether rapid functional adaptations would also occur with simultaneous changes in both target distance and size, which were selected so that ID remained constant.

5.1. Method

Three levels of task difficulty (ID 4–6) were defined by using an initial inter-target distance $D$ of 20 cm and initial targets sizes $W$ of 2.5, 1.25, and 0.625 cm. Because during experimental trials both $D$ and $W$ suddenly increased or decreased by 25%, a total of nine control conditions was necessary. These nine control conditions were randomly interspersed with six experimental conditions.

In the experimental conditions, the initial $D$ of 20 cm was suddenly increased by 25% ($D = 25$ cm) or decreased by 25% ($D = 15$ cm), by displacing both targets in opposite directions. At the same time, the initial value of $W$ (2.5, 1.25, or 0.625 cm) was also increased or decreased by 25%. Thus, ID remained constant over the change at a value of 4, 5 or 6, respectively.

5.2. Results

5.2.1. Control conditions

In accordance with Fitts’ law, movement time was longer for larger IDs, $F(2, 18) = 183.96, p < .001$ (577, 803, and 1092 ms for ID 4–6, respectively). The particular combination of $D$ and $W$ used to obtain a given ID did not influence the overall movement time, $F(2, 18) = 0.57, p = .57$. Thus, within the range of amplitudes and target sizes used, movement time was a function of ID only. Details on kinematic characteristics observed under the control conditions are provided in Table 1.

5.2.2. Experimental conditions

Analysis of the kinematic characteristics of the experimental trials during the “before” and “after” segments revealed that the patterns of movement were adapted to the task requirements. Whether before or after change, the kinematic characteristics were very close

| Table 1 |
|---|---|---|
| ID 4 | ID 5 | ID 6 |
| $D$ (cm) | 15 | 20 | 25 | 15 | 20 | 25 | 15 | 20 | 25 |
| $W$ (cm) | 1.875 | 2.500 | 3.125 | 0.938 | 1.250 | 1.563 | 0.469 | 0.625 | 0.780 |
| Amplitude (cm) | 14.89 | 19.85 | 24.76 | 15.05 | 20.00 | 24.89 | 15.11 | 20.09 | 25.07 |
| Movement time (ms) | 590 | 567 | 574 | 794 | 811 | 806 | 1079 | 1074 | 1123 |
| Peak velocity (cm/s) | 46.72 | 63.54 | 76.08 | 41.22 | 50.24 | 61.97 | 41.34 | 48.26 | 55.90 |
| Acc phase (ms) | 266 | 266 | 266 | 309 | 324 | 323 | 332 | 358 | 383 |
| Dec phase (ms) | 324 | 301 | 308 | 485 | 485 | 483 | 747 | 716 | 740 |
to those observed under the corresponding control conditions. No statistically significant differences were observed.

**Increase in distance and size.** As in Experiment 1, the simultaneous change in position of the two targets determined a two-step change in required amplitude. On A1, required amplitude increased from 20 to 22.5 cm. Amplitude of movement increased to reach the inside border of the new target (21.73 cm on average), leading to a somewhat larger amplitude for the higher IDs (21.02, 22.17, and 22.01 cm for ID 4–6, respectively; see Fig. 8, top panel). Peak velocity was unaffected during A1 (Fig. 8, middle panel), and thus the larger amplitudes were achieved by lengthening the deceleration phase, yielding an increase in the overall movement time (Fig. 8, bottom panel).

For A2, the required amplitude increased again, reaching 25 cm. Both the position and the size of the target for A2 were visually available already during A1. In line with the task requirements, the amplitude of movement increased to 24.01 cm, on average. However, in contrast to A1, the larger amplitude of movement was now achieved by an increase in peak amplitude, yielding an increase in the overall movement time (Fig. 8, bottom panel).
velocity and a return of movement time and deceleration duration towards baseline values. During subsequent aiming movements peak velocity tended to increase gradually while the duration of the deceleration phase and overall movement time continued to decrease gradually, reaching baseline values within three or four movements.

Decrease in distance and size. When the distance to the target decreased (and the target size decreased at the same time), the amplitude of movement also decreased. For A1, which required a change from 20.0 to 17.5 cm, the movement amplitude reached 18.50 cm on average, allowing participants to reach the inside borders of the targets (Fig. 9, top row). Similar to Experiment 1 (Fig. 4), this initial change in the extent of movement was not accompanied by a change in peak velocity (Fig. 9, middle row), or movement time (or its components) (Fig. 9, bottom row).

The second step in required amplitude (from 17.5 to 15.0 cm) gave rise to an average amplitude of movement for A2 of 16.20 cm. As observed in Experiment 1 (Fig. 4) and Experiment 2 (Fig. 7), the decrease in movement amplitude was accomplished by a decrease in...
peak velocity on A2. Interestingly, given that ID remained constant, the A2 movement time also increased briefly, due to a lengthening of both the acceleration and the deceleration phase, not unlike Experiment 2 (Fig. 7). During the subsequent movements, peak velocity stabilized and the temporal variables returned to their baseline values for the constant ID.

In sum, when both target distance and size were suddenly changed, there were transient increases in movement time. As in Experiment 1, increasing the required movement amplitude yielded a rapid lengthening of the deceleration phase during A1, followed by an increase in peak velocity on A2. Subsequently, movement time gradually returned to its original value for the constant ID. Decreasing the required movement amplitude evoked no adaptation on A1, but a decrease in peak velocity on A2, similar to Experiment 1. In addition, there was a transient increase in the overall movement time on A2 or A3, analogous to that observed when target size was reduced in Experiment 2.

6. Discussion

In a series of three experiments the present study analyzed adaptation of movement to sudden changes in task requirements during a reciprocal aiming task. The purpose was twofold. First, we sought to determine how participants adapted their movements in order to conform to new task constraints. Second, we sought to determine when changes in the pattern of movement occurred, so as to explore the time scale(s) of movement organization and to investigate the structuring role of information.

In order to interpret the changes in kinematic characteristics observed after a sudden change in either the distance $D$ to be covered (Experiment 1), the size $W$ of the target to be attained (Experiment 2) or both at the same time while keeping the index of difficulty (the ratio $D/W$) constant (Experiment 3), behavior was first analyzed under control conditions for all relevant combinations of $D$ and $W$, with no sudden changes. These control trials thus allowed us to characterize the stabilized behavior in particular task constraints.

In line with the literature, the kinematic pattern of movement was found to vary with variations in $D$ and $W$, such that participants tailored their movement pattern to the requirements at hand (Guiard, 1993; Mottet & Bootsma, 1999; Mottet et al., 2001). For tasks with a small ID, participants produced harmonic oscillations, with movement varying sinusoidally over time. Velocity profiles were symmetrically bell-shaped, with equal durations of the acceleration and deceleration phases. As task difficulty increased, systematic deviations from this harmonic pattern were observed, with the deceleration phase lengthening more than the acceleration phase. Velocity profiles thus became skewed to the right. The control conditions allowed us to determine the baseline values of kinematic variables for the set of task constraints. Adaptation to a sudden change in constraints could thus be evaluated.

In Experiment 1, target distance was manipulated by simultaneously displacing both targets in opposite directions. Participants were found to adapt the amplitude of their movement during A1 sufficiently to reach the new target. When the required amplitude increased, they did so by significantly lengthening the deceleration phase, leading to an increase in the overall movement time. This rapid adaptation indicated that visual information for task conditions was continually monitored. During A2, the amplitude of movement was adjusted by increasing peak velocity, indicating a more global adaptation of the kinematic pattern as a whole. When $D$ was decreased rather than increased, a similar global pattern of adaptation was observed, with peak velocity changing during A2.
In Experiment 2, target size was manipulated while maintaining the distance between target centers. When the target suddenly decreased from the largest to the smallest size, raising the precision demands, participants adapted their movement during A1 by a lengthening of the deceleration phase, leading to an increase in overall movement time. During A2 and the following movements, a gradual adaptation of the whole movement pattern was observed, with all kinematic characteristics progressively moving towards the baseline values corresponding to the new task constraints. When target size increased, rather than decreased, there was no need for rapid adaptation, for maintaining the same movement pattern would satisfy the new task requirements. In this case, no changes in kinematic characteristics were observed during A1. Temporal characteristics gradually evolved from A2 onward, while peak velocity shifted slowly towards the baseline values for the new task constraints. The absence of a rapid adjustment when it is not required underlines the functional nature of the adaptation. This result allows us to rule out the possibility that the rapid adjustment observed in A1 under other conditions is some sort of startle response induced by a change in the display.

In Experiment 3, both $D$ and $W$ were suddenly changed, such that the ratio of $D$ over $W$ – and hence the ID associated with the task – remained constant. Although the overall movement times before and well after the change were unaffected, the change induced a transient increase in movement time. As had been found in Experiment 1, increasing the amplitude of movement gave rise to an increase in movement time, while peak velocity remained unchanged during A1. During the following movements, peak velocity and the durations of the acceleration and deceleration phases progressively moved towards their baseline values for the new task requirements. As a result, overall movement time progressively returned to a value characteristic of the corresponding ID and independent of the particular combination of $D$ and $W$.

Overall, the adaptations observed during A1 extend the results reported by Heath et al. (1998) for discrete aiming movements to the case of continuous reciprocal aiming. Heath et al. (1998) interpreted the response to a sudden change in $D$ or $W$ in the framework of the two-component model (Elliott et al., 2001; Woodworth, 1899). According to this model, movement is organized in two phases. An initial ballistic phase drives the end-effector in the direction of the target. During the ensuing current control phase, visual feedback allows adjustments to be made to the ongoing movement. The finding that a sudden change in task requirements does not affect the duration of the acceleration phase or the peak velocity fits with the proposition that the acceleration phase is (part of) a ballistic phase. Adjustments occurring during deceleration onto the target are consistent with the proposition that (part of) the deceleration phase is under visual feedback-based control.

The adaptations observed during A1 in our reciprocal aiming task closely resemble those observed by Heath et al. (1998), and could therefore be interpreted as further evidence for the two-component model. However, we contend that the two-component model cannot easily be extended to include continuous movement patterns and is thus not an adequate theoretical framework for interpreting the data from both discrete and continuous aiming tasks. For low levels of ID we systematically observe a harmonic oscillation, with the deceleration phase of one movement being fully merged with the acceleration phase of the next (Bootsma et al., 2002; Fernandez & Bootsma, 2004; Guiard, 1993; Mottet & Bootsma, 1999; Mottet et al., 2001). The left columns of Fig. 1 graphically present such a pattern of movement. The deceleration that will bring the velocity to zero (within the target zone) and the subsequent re-acceleration to move the cursor to the next target are thus part
of a single acceleration burst. The fact that at some point the velocity changes direction does not imply that deceleration (just before) and re-acceleration (just after) are to be attributed to different control mechanisms. By analogy, the movement pattern under low levels of ID can be compared to the motion of a pendulum (or a mass-spring system) where gravity (or the spring force) decelerates the motion as the system approaches its extremity before, by the same physical process, re-accelerating in the opposite direction. Clearly, the distinction between a ballistic phase and a current control phase, derived from the analysis of discrete movements, cannot be applied to harmonic oscillations. When ID is increased, the movement pattern gradually loses its harmonic character (Guiard, 1993; Mottet & Bootsma, 1999). In terms of deceleration and re-acceleration, a gradual dissociation of deceleration and re-acceleration is observed. However, it is not until a full dissociation occurs (that is, until deceleration becomes zero at the movement extreme, before a new acceleration burst drives the effector towards the new target) that one can distinguish, in a sequential logic, the deceleration from the subsequent re-acceleration. An example of such a pattern of movement is presented in the right columns of Fig. 1.

We therefore propose an alternative framework for understanding the observed adaptations. Mottet and Bootsma (1999) demonstrated that the stabilized patterns of movement as observed under different conditions of task requirements can be interpreted in terms of the modulation of the parameters of an otherwise invariant dynamical system that underlies the organization of movement. Expressing this dynamical structure as an equation of motion, Mottet and Bootsma were able to reproduce the variety of kinematic patterns observed under 25 different combinations of $D$ and $W$ by modifying four parameters of their model. In the present experiments, we showed that a sudden change in task requirements leads to a transformation from one such kinematic pattern to another, which can thus be modeled by an appropriate modulation of parameters. The phenomena of adaptation can therefore be captured at the level of the parameter dynamics. Although the present experiments were not designed to test a sufficiently large number of trials per participant to fit Mottet and Bootsma’s (1999) model, they permit a qualitative interpretation of the adaptation process.

The results suggest that an interpretation in terms of two similar concurrent processes, specifically two parameter dynamics with different time scales, is more appropriate than the interpretation of two different processes operating sequentially (see O’Dwyer & Neilson, 1996, 1998, for a similar conclusion within a different framework). From this perspective we observe the following: a rapid, transient component, allowing the action to quickly comply with the new task constraints, and a slower, more gradual component that tailors the whole kinematic pattern to the requirements at hand. In the terms of dynamical systems, the short time-scale adaptation may result from discrete parameter resetting, as a type of emergency procedure. The longer-term reshaping of the global kinematic pattern (i.e., the limit cycle) results from a slower parameter dynamics.

Parameter resetting has been used to model the effects of mechanical perturbations (Kay, Saltzman, & Kelso, 1991; Mottet, Beek, & Bootsma, 2004). Based on simulation results, Zaal, Bootsma, and Van Wieringen (1999) suggested that amplitude of movement was associated with the magnitude of a non-linear damping (i.e., velocity-dependent) parameter. Rapid changes in amplitude could thus be brought about by resetting this parameter value. On the other hand, when comparing stationary conditions, Mottet and Bootsma (1999) (Fernandez, 2004) reported that parameter values co-varied in a systematic manner. Thus, rapid adaptation might be obtained by modifying a single parameter,
while more global adaptation would imply (re-)establishing relations between parameters as appropriate for the new task demands. Further experimentation and simulation studies are needed to resolve this issue.

The existence of rapid adaptations during A1 indicates that visual information about task constraints is monitored and used to modulate the underlying dynamic. In all three experiments, the pattern of movement produced under the lowest levels of difficulty (ID 4) was a basic, harmonic oscillation between targets. The harmonicity of the pattern is indicative of the facility of execution, suggesting that participants could perform such oscillatory movements in an automatic mode, without relying on visual feedback (Zelaznik, Hawkins, & Kisselburgh, 1983). Yet the rapid adaptations observed even under these conditions clearly indicate that information about the target is picked up during each half-cycle of movement. The absence of rapid adaptation when it was not necessary (e.g. with increasing target size in Experiment 2) indicates that information about the adequacy of the unfolding movement with respect to the constraints of the task is continuously being evaluated, leading to adaptation of the movement at a faster and/or slower time scale, as appropriate.

We conclude that, during reciprocal aiming, information is monitored and influences the organization of movement by modulating the parameters of an otherwise invariant dynamic. Visual information specifies the required change of movement in task space, yielding adaptation on two time scales: a short-term adjustment to meet the new task constraints in the first half-cycle, and a long-term change of the kinematic pattern as a whole over several cycles. A similar pattern of results was reported by O’Dwyer and Neilson (1996) for a tracking task with stepwise changes in target position. In the present context we attribute these effects to a discrete resetting of an amplitude-related parameter, followed by the slower adjustment of a set of parameters to reshape the global movement pattern for the new task conditions.

References


