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Correcting slightly less simple movements

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Many studies have analysed how goal directed movements are corrected in response to changes in the properties of the target. However, only simple movements to single targets have been used in those studies, so little is known about movement corrections under more complex situations. Evidence from studies that ask for movements to several targets in sequence suggests that whole sequences of movements are planned together. Planning related segments of a movement together makes it possible to optimise the whole sequence, but it means that some parts are planned quite long in advance, so that it is likely that they will have to be modified. In the present study we examined how people respond to changes that occur while they are moving to the first target of a sequence. Subjects moved a stylus across a digitising tablet. They moved from a specified starting point to two targets in succession. The first of these targets was always at the same position but it could have one of two sizes. The second target could be in one of two different positions and its size was different in each case. On some trials the first target changed size, and on some others the second target changed size and position, as soon as the subject started to move. When the size of the first target changed the subjects slowed down the first segment of their movements. Even the peak velocity, which was only about 150 ms after the change in size, was lower. Beside this fast response to the change itself, the dwell time at the first target was also affected: its duration increased after the change. Changing the size and position of the second target did not influence the first segment of the movement, but also increased the dwell time. The dwell time was much longer for a small target, irrespective of its initial size. If subjects knew in advance which target could change, they moved faster than if they did not know which could change. Taken together, these results suggest that the whole sequence is treated as one action, which can be corrected if the properties of any of the targets change. The precise nature and timing of the correction depends on how the change influences the task.

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When we execute a movement towards an object, such as reaching for a pen on our table, we seldom expect the properties of this object to change during our movement. However, because our movement takes time to be executed, there are circumstances in which properties such as the object's position do change. We could, for example, hit the leg of the table with our foot and make the pen roll. When this happens we correct the movement of our hand and pick the pen up from its new position. Many studies have analysed the changes in movement kinematics that occur when such corrections take place.

When goal-directed movements are corrected in response to changes in target properties, the total duration of the movement often increases. This has been found to occur after changes in target *position* (e.g. Fecteau, Chua, Franks & Enns, 2001; Heath, Hodges, Chua & Elliott, 1998; Paulignan, MacKenzie, Marteniuk & Jeannerod, 1991; Prablanc & Martin, 1992), in target *size* (e.g. Castiello, Bennett & Stelmach, 1993; Paulignan, Jeannerod, MacKenzie & Marteniuk, 1991), or in both *size and position* simultaneously (Castiello, Bennett & Chambers, 1998). The increase in movement time is usually caused by a longer duration of the deceleration phase of the movement (Castiello et al., 1993; Castiello et al., 1998; Fecteau et al., 2001; Heath et al., 1998; Prablanc & Martin, 1992; Paulignan, Jeannerod, et al., 1991), sometimes accompanied by a decrease in peak velocity (e.g. Fecteau et al., 2001). One problem that arises when manipulating target position is that the distance that the hand moves to reach the target is usually changed by the manipulation. After correcting for the longer trajectories, some authors have found no increase in the duration of the movement (e.g. Goodale, Pélisson & Prablanc, 1986; Pélisson, Prablanc, Goodale & Jeannerod, 1986), while others still found an increase in the duration of the movement (Prablanc & Martin, 1992).

Changing target properties during a movement has been used to estimate the amount of time that the motor system needs to react to a disturbance. The minimal amount of time needed to start correcting an on-going goal-directed hand movement after the *displacement* of a target has been estimated to be about 110 msec. (Brenner & Smeets, 1997; Day & Lyon, 2000; Prablanc & Martin, 1992; Soechting & Lacquaniti, 1983). However, there are circumstances under which more time is needed. For example, reaction times of around 200 msec or longer have also been found for similar manipulations (Day & Lyon, 2000; van Sonderen, Denier van der Gon & Gielen, 1988). The time needed to respond to a change in position may also depend on the direction (Elliott, Lyons, Chua, Goodeman & Carson, 1995; Paulignan, MacKenzie, et al., 1991) and the predictability (Boulinguez & Nougier, 1999) of the displacement. Changes in target *size* may even take as much as 330 msec to respond to (Paulignan, Jeannerod, et al., 1991). For simultaneous changes of size and position, Castiello et al. (1998) found a reaction time of 400-460 msec. All these results suggest that there are considerable limitations on how quickly we can react to new visual information.

One possible limitation that has not yet been analysed is movement complexity. This aspect could be relevant because previous results have shown that it takes longer to react to a change in a target's colour if the task can be considered complex (abort the movement towards the target if it changes colour but adjust your movement if it only changes position; Pisella, Arzi & Rossetti, 1998) than if it is evidently simple (tap the red target irrespective of whether it moves; Brenner & Smeets, 2004). Complexity has also been found to influence various other movement characteristics, like for example reaction time (Christina, Fischman, Vercruyssen & Anson, 1982; Fischman, 1984; Smiley-Oyen & Worringham, 1996). In the previous paragraph experiments were mentioned in which very fast reactions were found. In all those experiments subjects had to move their hand to a single target, which could be perturbed in only one of a few simple ways. If such fast reactions only occur under such simple conditions they will seldom occur in daily life, where most of our movements are more complex, involving more than one target. For example, if we want to drink some coffee, we move our hand to grasp the cup, but the target of the action is not the cup. Grasping the cup is a prelude to moving it towards our mouth to drink. In this example, our mouth is the real target of the sequence of hand movements. Of course this sequence could be considered to consist of several separate, independent movements, each with its own target and control. However there is evidence that sequences of movements are not controlled in this manner.

It is known that movements towards a single target are faster than movements that are part of a sequence that continues to a second target. This has been called the “one-target advantage” (e.g. Adam et al, 2000). Various experiments have also shown that the kinematics of the first part of a sequence of two movements depends on the difficulty of the second part. For example, Rand, Alberts, Stelmach and Bloedel (1997) asked subjects to move a stylus to two targets in sequence. They found that the duration of the movement to the *first* target depended on the size of the *second* target, even though the size of the first target and the distances between the targets were identical in all cases. Similar results have been found with other paradigms (Adam et al., 1995; Lajoie & Franks, 1997; Rand & Stelmach, 2000) and with other tasks (e. g. for grasping: Gentilucci, Negrotti & Gangitano, 1997). These results have been interpreted as suggesting that both movements of the sequence are planned before movement initiation, considering the properties of the two targets. When the first target is very small, and therefore difficult to hit, the interaction between the targets disappears, and the dwell time between the movements is longer (Adam, et al., 1995; Rand and Stelmach, 2000). In that case each movement is presumably planned and controlled separately.

If the two movements of a sequence are planned considering the properties of both targets, then we would expect visual information about both targets to be used for the on-line control of the movement as well. If that is so, then a change in the properties of *either* of the targets could give rise to a fast reaction or correction. To find out when and how subjects correct their movements under such circumstances, we designed experiments in which subjects were required to make a sequence of two movements, and manipulated the properties of the two targets during the execution of the first movement. Subjects were asked to move a stylus from a specified starting point to two targets in succession. The first of these targets was always at the same position, but it could have one of two sizes. The second target could be in one of two different positions and its size was different in each of these cases. On some trials, as soon as the subject started to move, the first target changed size. On others there was a change in the size and position of the second target. We performed three experiments in which the first target, the second target, or both could change.

If the whole sequence of movements is planned in advance, before movement initiation, then an analysis of the kinematics of the movements will show that both targets' properties are taken into account. If both targets are also relevant for the on-line control of the movements, then a change in the properties of either of the targets could affect the kinematics of the first movement (if the response is fast enough).

METHOD

Participants. 10 subjects (seven males and three females; ages ranging from 26 to 47 years) participated in all three experiments. Two of them were authors of this paper, and the other eight were colleagues from the department. They all had previous experience with similar tasks, but, except for the authors, were naive about the purpose of the present experiments. All participants had normal or corrected to normal vision, reported to be right-handed, and had no known neuromuscular deficits at the moment the experiments were run. This study is part of an ongoing research project that has been approved by the local ethics committee.

Apparatus and task. Subjects sat comfortably in a chair in front of a graphic tablet (Wacom A2) which recorded two-dimensional position data at a frequency of 200 Hz. The stimuli were projected onto the tablet using a projector. The resolution of the display was 1024x768 pixels. Each pixel corresponded with approximately 0.5 mm on the surface of the tablet. Subjects were instructed to hold a stylus in their right hand. They had to slide the stylus across the tablet to perform the movements. At the beginning of each trial, subjects saw a small dot on the near left side of the tablet. This was the starting position. Once the stylus was placed at this position, two differently coloured targets were projected onto the tablet. Subjects were asked to move the stylus from the starting position to the red target first, and then to the black target. They were asked to do so as fast as possible. Both targets were circles, which could have one of two different sizes: a diameter of 4 cm or 0.8 cm. The first target was always situated 20 cm to the right of the starting position. The second target was situated at one of two different positions relative to the first target (see Figure 1). The two positions differed in both distance and direction. The second target was either 5 cm from the first with the two movements forming an angle of approximately 53° (*second target close*); or else it was 23.5 cm from the first with the two movements forming an angle of approximately 140° (*second target far*). The combinations of size and position of the second target (including the partial reversal of the movement) were chosen to maximise the expected influence on the speed of the first movement.

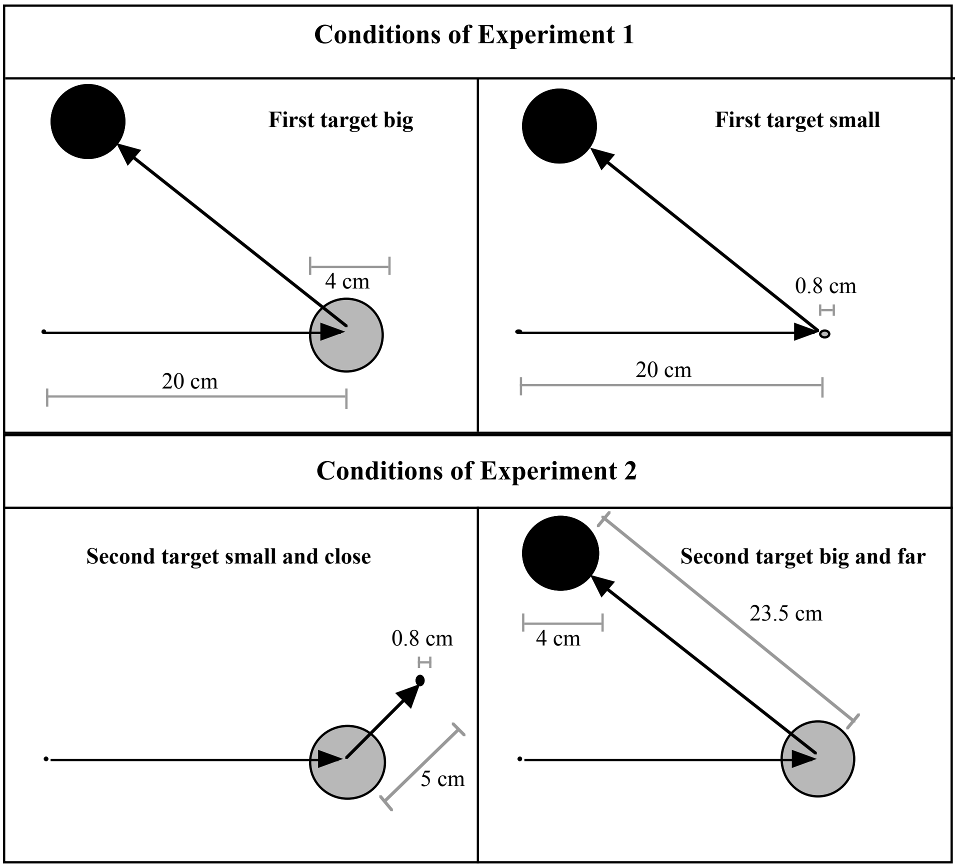

Figure 1. Experimental setup. Once subjects placed the stylus at the starting position (small dot on the left), both targets were projected from above onto the graphic tablet. The first, red target (shown here in grey) was 20 cm to the right of the starting position. In the first experiment it could be either big (4 cm diameter) or small (0.8 cm diameter). In the second experiment it was always big. In the first experiment the second, black target was big and at the far left of the tablet, 23.5 cm from the first. In the second experiment the second target could either be big and at that far left position, or small and close to the first target (5 cm from the latter). In the third experiment all the conditions of the first two experiments were combined in a random order.

To ensure fast performance, a message prompting subjects to speed up their movements was heard whenever a trial (whole sequence of two movements) lasted longer than 900 msec (in Experiments 1 and 3) or 750 msec (in Experiment 2). The maximal movement time, as indicated by presenting this message, was reduced for Experiment 2 in an attempt to equate the (subjective) difficulty to that for the trials with a small first target in the other two experiments. Although subjects were prompted to move faster when their movements took longer than the above-mentioned maximal movement time, slower trials were neither repeated nor eliminated from the analysis. Subjects also received a message if they missed the first target. This was considered to be the case if the velocity did not decrease to below 5 cm/sec within the confines of the target. The message was only presented to remind subjects to be accurate, because all trials were included in the analysis, including those in which subjects missed the target.

Experimental conditions. Table 1 summarises the conditions used in each of the three experiments. The trials of the different conditions within each of the experiments were presented in random order. The manipulations consisted of a change in the position and/or size of one of the targets once the movement towards the first target started (defined as the moment at which the velocity reached a threshold of 5 cm/sec). A manipulation was introduced in 20% of the trials.

In Experiment 1, the first target could have one of two sizes at the beginning of the movement: in half of the trials the target was small (0.8 cm) and in the other half it was big (4 cm). The second target was always situated at the far position, and its size was 4 cm. The configuration of the targets for this experiment can be seen in the upper part of Figure 1. The manipulation consisted of the first target changing from being small to big, or vice versa.

In Experiment 2, the first target was always big (4 cm) and at the same position. The second target was initially at the close position on half of the trials and at the far position on the other half. When the target was at the close position it was small (0.8 cm). When it was at the far position it was big (4 cm). The configuration of the targets for this experiment can be seen in the lower part of Figure 1. The manipulation consisted of the second target jumping to the other possible position, from near to far or vice versa, and changing size accordingly.

In Experiment 3 all the conditions of Experiments 1 and 2 were presented. They were randomly interleaved to reduce the predictability of the change. Previous results (Boulinguez & Nougier, 1999) have shown that movement corrections after a manipulation of the target are faster when participants know the most probable direction of the manipulation. In Experiments 1 and 2 only one target was manipulated, so subjects were able to predict in which way they would have to correct their movements if a change occurred. In Experiment 3 we made the first and the second target equally relevant by mixing all the conditions of the first two experiments: either target could change on a given trial, and the change always took place before the subject had reached the first target.

Table 1. Description of the size and position of the different targets in the different conditions of the three experiments, together with the number of trials run for each condition. "Target 1" and "Target 2" are the first and second targets. When there was a change both the initial (*before*) and final (*after*) position of the target are given. The conditions indicated with the asterisks are identical, but they were treated as two separate conditions during Experiment 3 to maintain the same proportion of trials with and without changes as in Experiments 1 and 2.

Target 1 (T1) (before / after change)	**Target 2 (T2) (before / after change)**	**Number of trials**		
		Exp. 1	**Exp. 2**	**Exp. 3**
Small	Big and Far	40	--	40
Big	Big and Far	40	--	40 *
Small / Big	Big and Far	10	--	10
Big / Small	Big and Far	10	--	10
Big	Small and Close	--	40	40
Big	Big and Far	--	40	40 *
Big	Small and Close / Big and Far	--	10	10
Big	Big and Far / Small and Close	--	10	10

Data analysis. The separations between consecutive raw x-y positions were used to obtain tangential velocity profiles for each movement. No filtering or smoothing algorithms were applied, except for a simple algorithm for interpolating occasional single missing data points. The velocity profiles were used (in a two-step analysis) to isolate two movements, one ending at each of the targets. First, two peaks were extracted from the velocity profile by finding sections for which the velocity was above a given threshold. This threshold was between 15 cm/sec (for the slowest subjects) and 30 cm/sec (for the fastest subjects). Once the moments at which the velocity crossed the threshold had been established, the beginning and end of each movement were found by looking backwards or forwards from these moments until the criteria for onset or offset were met. For the beginning of the first movement, we looked backwards until we found 5 consecutive points with a velocity of zero. The last point before this (i.e. the first with a value larger than zero) was taken as the beginning of the movement. Similar requirements were used to find the end of the second movement. To define the end of the first movement we searched forward from the moment that the velocity declined below the threshold, either until we found two consecutive points with the same position (i.e. a velocity of zero) or until the velocity started to increase again (i.e. until the first local minimum). Similarly, the beginning of the second movement was found by searching backwards for the first point with velocity zero, or for the last local minimum before the second movement.

Once the starting and end points of each movement were found, as well as the moment of peak velocity, the following measures were calculated: the duration of each movement (first and second), the peak velocity of the first movement, the duration of the acceleration and deceleration phases of the first movement, the dwell time (at the first target), and the lateral and sagittal coordinates of the end positions at the first target.

Trials with errors in the recording and ones in which the velocity profile did not show two clear peaks were discarded from the analysis (about 3% of the trials in Experiment 1, 4.5% in Experiment 2, and 2% in Experiment 3). This included trials in which the second target's position changed, but the movement was not adjusted, so that the hand was initially directed towards the old position of the target, and only later moved towards the new position, which gave rise to three velocity peaks.

Statistical analysis. As can be seen in Figure 1, the position of the first target was identical under all conditions and in all experiments. If there were no effects of either the initial properties of the targets or their manipulation, we would expect the kinematics of the movement towards this target to be identical in all cases. We therefore compared the kinematics of the movements towards the first target on trials with different targets, and compared trials in which there was no change with ones in which either the first or the second target changed. For the statistical analysis we divided the trials into two groups, depending on whether the manipulation affected the first target (Experiments 1 and 3) or the second target (Experiments 2 and 3).

Since the same conditions were presented in Experiment 3 as in Experiments 1 and 2, we could combine the analysis of Experiment 3 with that of the other two experiments by adding the experiment (i.e. the number of possible changes) as an independent variable. The dependent variables were the measures that were mentioned in the previous section. Each dependent variable in each group of data was subjected to an independent repeated measures analysis of variance (ANOVA). The mean values of each measure for each subject were used as the dependent variables, except for the end positions, for which we analyzed the standard deviations. Three factors were included in each ANOVA: Initial Target Properties (*big* versus *small*, or *small and close* versus *big and far*), Manipulation (*no change* versus *change*), and Experiment (*1 or 2* versus *3*).

We expected a significant effect of the first factor, *target properties*, because the initial properties of the two targets were selected to give an effect. We expected to confirm that the kinematics of the first movement depends on the size of the first target (Fitts' Law), and also that the properties of the second target influence the kinematics of the movement towards the first target (Adam et al., 1995; Rand et al., 1997; Rand & Stelmach, 2000). A significant effect of the last of the above-mentioned factors, *Experiment*, for the first group of data (changes in the first target' size) could indicate that subjects consider the changes that are likely to occur when controlling their movements. The properties of the first target and the changes to that target are identical for Experiments 1 and 3. The only difference is the possibility that the second target changes, which is present in the trials of Experiment 3, but not in those of Experiment 1. A similar effect of the factor *Experiment* for the second group of data (changes in the second target' size and position) cannot be attributed to the possibility that the first target changes, because it could be the result of the different time constraints used (for the feedback) in the two experiments. An interaction between *Manipulation* and *Experiment* would indicate that the response to a change depends on the predictability of the change.

Our main interest was in possible significant effects of the second factor: *Manipulation* of the target properties. In one group of trials the manipulation was an occasional change in the size of the first target. In the other group it was an occasional change in the size and position of the second target. By comparing the kinematics of the first movement in trials with and without a change, we wanted to see whether subjects were able to react to the manipulation and, if so, how fast they could do so. We expected changes to the first target to influence the movement towards that target, but will changes to the second target also influence the first movement?

RESULTS

Movement Time.

In Figure 2 we show mean values of the total duration of the movement towards the first target. The left side of the figure shows this for the trials in which the first target's size did or did not change (Experiment 1 and half of the trials of Experiment 3). The right side shows this for the trials in which the size and position of the second target did or did not change (Experiment 2 and the other half of the trials of Experiment 3). Each part is also subdivided into two, to separate trials without and with a change. Data from Experiment 1 are represented by solid squares and dotted lines, data from Experiment 2 by solid triangles and dotted lines, and data from Experiment 3 by open circles and continuous lines. Subsequent plots use a similar structure and the same symbols.

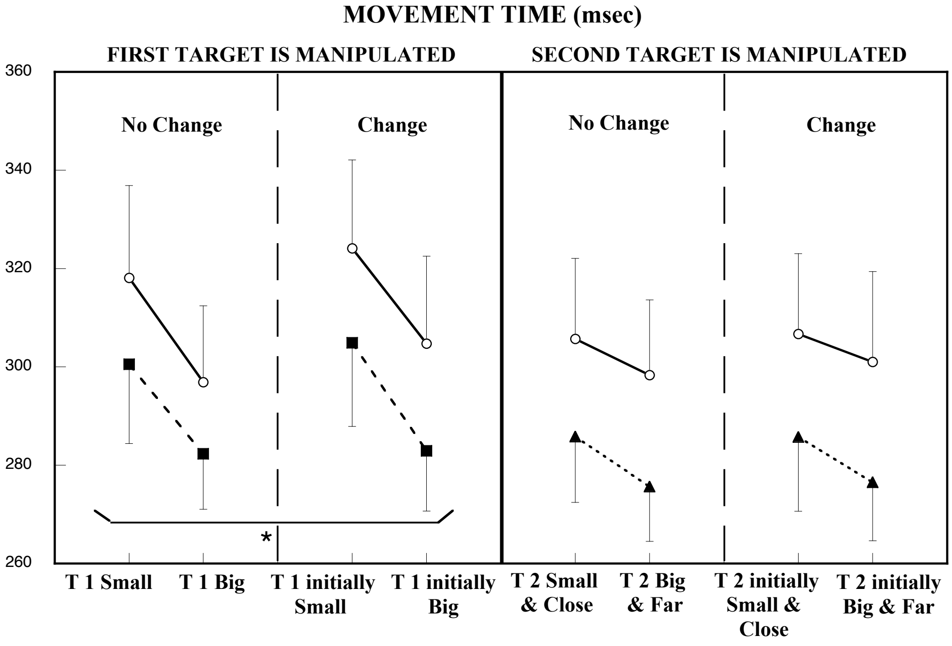

Figure 2. Total duration of the movement to the first target (in milliseconds). Squares show data from Experiment 1, triangles data from Experiment 2, and circles data from Experiment 3. Error bars show between-subject standard errors. The asterisk indicates a significant main effect of change.

Our expectation that both targets properties would influence the kinematics of the first movement was confirmed. There was a significant effect of the size of the first target (p=0.001) and of the size and position of the second target (p=0.008). As was to be expected, the movement towards a small first target took longer than that towards a big first target. When the second target was small and close, the movement to the first target took longer than when the second target was big and far.

When the first target changed size there was a significant increase in the duration of the first movement (p=0.04). This increase occurred both when the target became smaller and when it became bigger. Thus it appears to be a general slowing down of the movement in response to a change, rather than an adaptation to the new size of the target. When the second target changed size and position there was no effect on the duration of the movement to the first target. For both of the groups of trials the difference between the experiments was significant (p=0.04 for Experiments 1 and 3; p=0.04 for Experiments 2 and 3). In both cases subjects were slower in the third experiment. None of the interactions were significant.

The duration of the second movement depended on the final properties of the second target. When the second target was small and close the second movement had an average duration of about 290 msec. When the second target was big and far the average duration of the movement was 433 msec. None of the manipulations had a significant effect on the duration of the second movement, so we did not analyze the second movement any further.

Duration of the Acceleration phase.

Figure 3 shows the duration of the acceleration phase for the different conditions of the three experiments. As was to be expected on the basis of the analysis of the movement time, the movement towards the first target was significantly longer both when the first target was small (p=0.001) and when the second target was small and close (p=0.003). We did not expect to find any adjustments to the movement so soon after the change, and indeed we found no significant influence of a change in either target's properties. There were no significant differences between the trials of the different experiments either (1 vs. 3, or 2 vs. 3). None of the interactions were significant.

Duration of the Deceleration phase.

The mean durations of the deceleration phase of the movements towards the first target are presented in Figure 4. The deceleration phase was significantly longer when the first target was small (p=0.005) and when the second target was small and close (p=0.03). Thus the whole movement appears to be scaled in relation with the properties of both the first and the second targets of the sequence. When the size of the first target changed, there was a significant increase in the duration of the deceleration phase (p=0.03). As we saw for the total movement time, a similar effect was found when target size increased as when it decreased. This means that the response cannot be explained as a switch between two movement patterns. When a change in the properties of the second target was introduced there was no effect on the duration of the deceleration phase of the first movement. Again there were significant differences between the experiments (p=0.03 for both comparisons), and none of the interactions were significant.

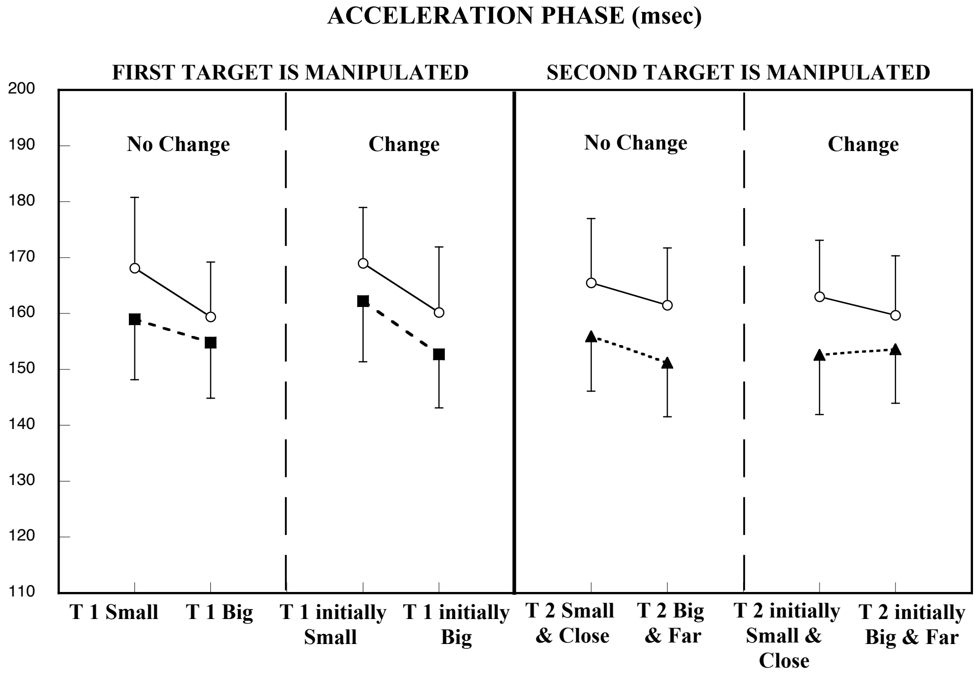

Figure 3. Duration of the acceleration phase of the first movement (in milliseconds). Squares show data from Experiment 1, triangles data from Experiment 2, and circles data from Experiment 3. Error bars show between-subject standard errors.

Peak velocity.

Figure 5 shows the mean peak velocities for each condition. There was a significant effect of the properties of both the first (p=0.00007) and the second (p=0.0006) target. Peak velocity was lower when the first target was small, and also when the second target was small and close. We found no significant influence of changing the second target, but changing the size of the first target decreased peak velocity significantly (p=0.04). There were also significant differences between the experiments (p=0.04 for Experiment 1 vs. 3; p=0.01 for Experiment 2 vs. 3). Subjects were slower in Experiment 3. None of the interactions were significant.

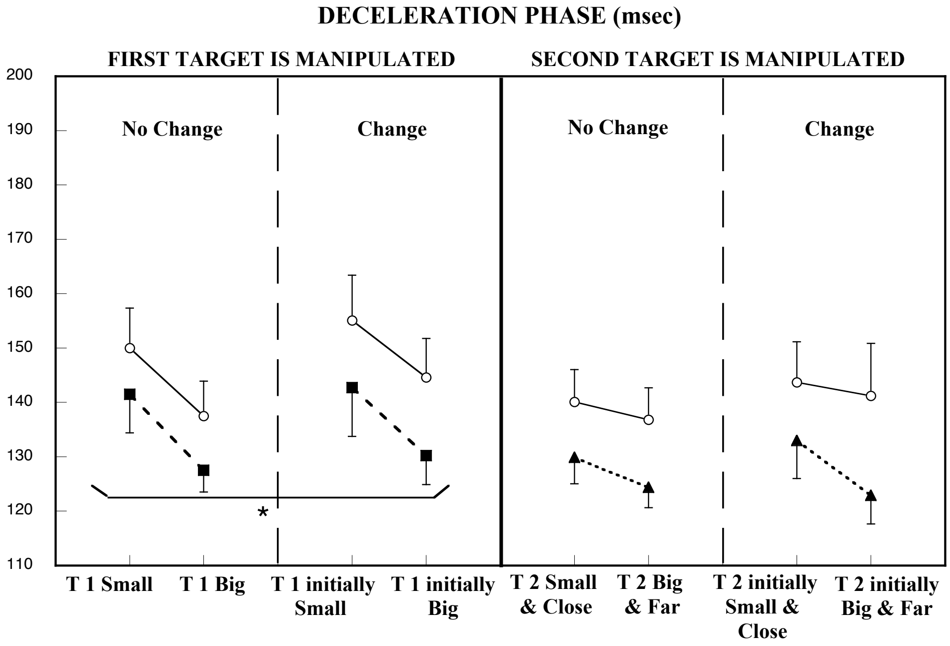

Figure 4. Duration of the deceleration phase of the first movement (in milliseconds). Squares show data from Experiment 1, triangles data from Experiment 2, and circles data from Experiment 3. Error bars show between-subject standard errors. The asterisk indicates a significant main effect of change.

Dwell time.

The dwell time, the time that the hand remained at the first target between the two movements, is shown in Figure 6. We observed an increase in dwell time both when the first target changed size ($p<0.001$) and when the second target changed size and position ($p=0.001$). Interestingly, for the first group of trials (changes in first target) the interaction between the initial size of the first target and the presence of a change was significant ($p<0.001$). The dwell time was much longer whenever the first target was small at the end of the trial. Thus in this case, by the end of the movement, the “new size” of the first target determined the performance, rather than the one at the beginning of the trial. In this case participants were clearly adjusting their movements to the new conditions. Note that in addition to this very clear adjustment, the dwell time was also consistently larger when there was a change. There was no significant effect of the factor Experiment, and there were no other significant interactions.

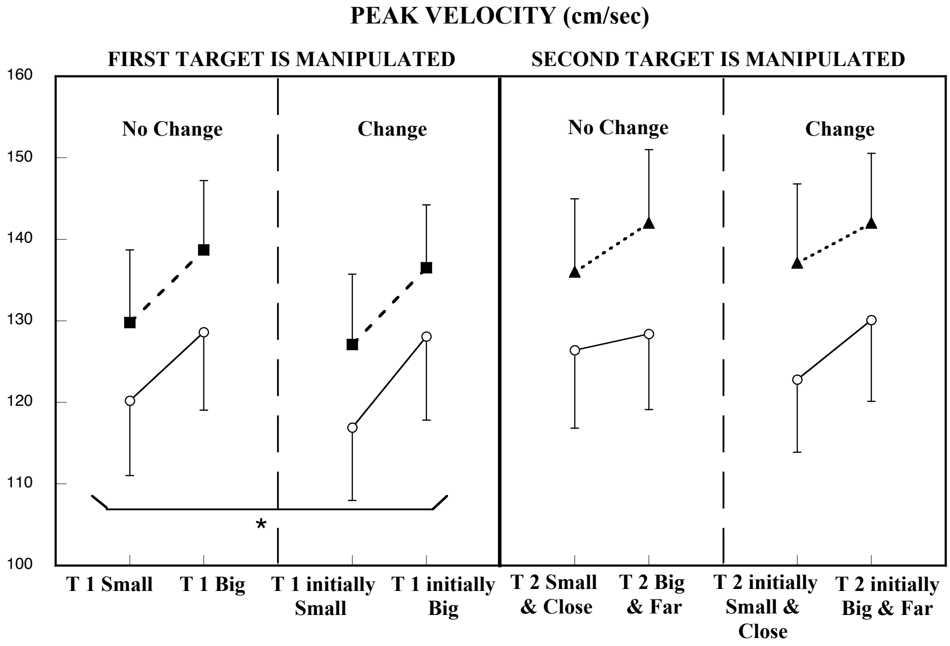

Figure 5. Peak velocity of the movement towards the first target (in cm per second). Squares show data from Experiment 1, triangles data from Experiment 2, and circles data from Experiment 3. Error bars show between-subject standard errors. The asterisk indicates a significant main effect of change.

Variability of the end positions.

Figure 7 shows the mean standard deviations of the first movements' endpoints for each of the conditions. Both the lateral and the sagittal variability were analysed. A significant effect of the initial size of the first target was found for the variability in the sagittal direction (p=0.0001), but there were no significant effects of change. This means that the variability of the end positions of the first movement did not vary after a change in the size of the first target, although, as we saw previously, the dwell time depended on the new size of the target after the change. A similar effect of the initial size of the first target can be seen for the lateral direction, although it was not significant (p=0.066). Neither the properties of the second target, nor their manipulation during the trial, had a significant effect on the variability of the end positions. There was no significant effect of Experiment, and none of the interactions were significant.

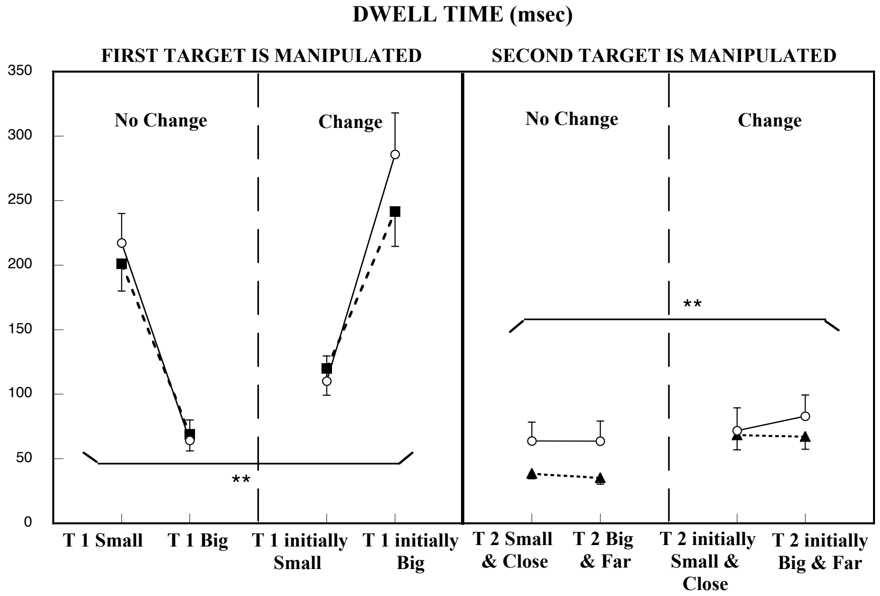

Figure 6. Dwell time between the movements (in milliseconds). Squares show data from Experiment 1, triangles data from Experiment 2, and circles data from Experiment 3. Error bars show between-subject standard errors. The asterisks indicate significant main effects of change. Note that the axis encompasses a much longer range of times than in Figures 2, 3 and 4.

DISCUSSION

Our experiments were designed to analyze how subjects responded to a change of the properties of one of the two targets in a sequence of movements. We also examined how the initial properties of these targets affected the movement. Our results showed that movement kinematics depends both on the size of the first target, and on the size and position of the second target. When the first target was small, the total duration of the movement (both the acceleration and deceleration phase) was longer, and peak velocity was lower. This result is consistent with what would be expected from Fitts' Law. When the second target was small and close, the total duration of the first movement was longer. This result is consistent with earlier findings (e.g. Adam et al., 1995; Rand et al., 1997; Rand & Stelmach, 2000) and suggests that both movements in the sequence are planned simultaneously, considering the properties of both of the targets.

Our main interest was to analyze how subjects would react to a change in the properties of the targets when they had to move to two targets in sequence. The changes could affect either the first or the second target in the sequence. When the properties of the *first* target changed, the kinematics of the movement towards the first target changed: peak velocity decreased and the duration of the deceleration phase increased. When the properties of the *second* target changed, the kinematics of the movement towards the first target did not change.

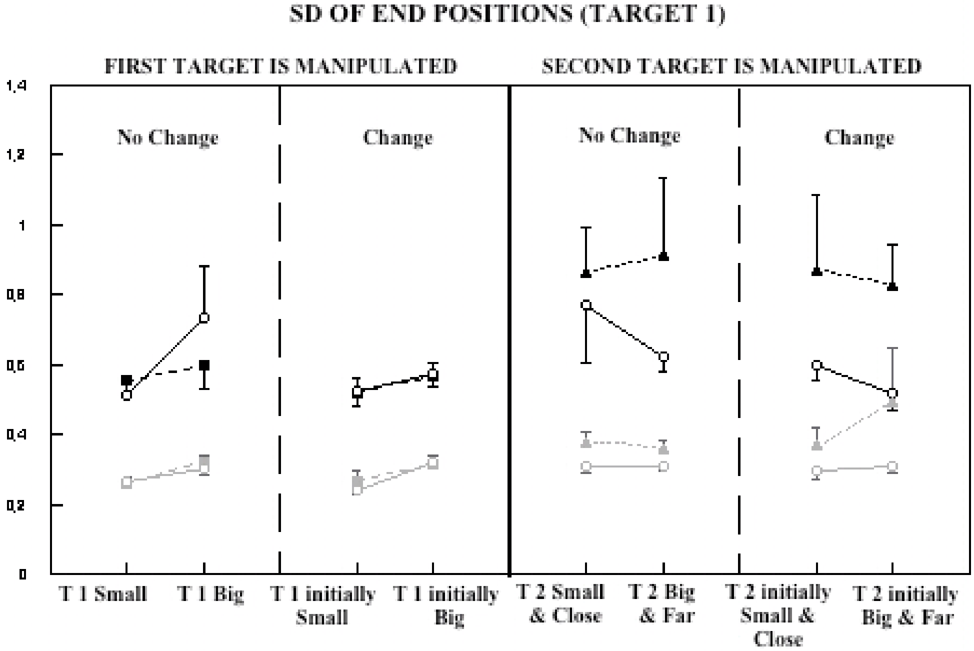

Figure 7. Standard Deviations of the end positions of the movements towards the first target (in cm). Black symbols are for the lateral direction and grey ones for the sagittal direction. Squares show data from Experiment 1, triangles data from Experiment 2, and circles data from Experiment 3. Error bars show between-subject standard errors.

The most interesting result that we found is that the manipulation of the properties of *either* of the targets produced an increase in the duration of the dwell time. When either the first or the second target changed there was a significant increase in the duration of the dwell time. The increase in the dwell time after a change in the size and position of the second target could be interpreted as resulting from the need to re-plan the second movement. However, this is unlikely to be the cause, because there was an even higher increase in the dwell time after the size of the first target changed. In that case it was not necessary to change the planned second movement, because that movement did not change. It seems more likely that the increase in the duration of the dwell time is a direct reaction to the change itself. The increase may be related to a need to check whether the movements have to be changed, rather than to the need to implement changes in the movement after the manipulation.

In accordance with previous studies (Adam et al., 1995; Adam & Paas, 1996; Rand & Stelmach, 2000), we found that the dwell time was significantly longer when the first target was small. The long dwell times appeared not only when the first target was small during the whole trial, but also when the first target became small after a change of size took place. Thus the duration of the dwell time depended on the size of the first target *during* the first movement. However, although the movement time and the dwell time had adapted to the new properties of the target by the end of the first movement, the adaptation was not complete, because we did not find a corresponding effect on the variability of the end position of the first movement. The standard deviations of the end positions were similar in trials with and without a change, and depended on the *initial* size of the first target, despite the fact that the movement time had increased. This too suggests that the change in movement time after a change in target size is more likely to be related to evaluating the whole sequence of movements, than to be a direct adaptation to the new spatial requirements.

Although the adaptation of the movement to the new target' properties was not complete in our experiments, we found that our subjects reacted very quickly when there was a change in the size of the first target. It is difficult to estimate how long after the change they reacted, because the first target did not change position and so there were no changes in the trajectory that could be used to determine the reaction time (as has been done in previous studies). However we found significant differences in peak velocity between trials with and without a change. This means that subjects were able to react to the manipulations before peak velocity. On average peak velocity was reached approximately 150 msec after the manipulation. Thus our experiments demonstrate that fast responses can occur for changes in size, as well as for changes in position (contrary to the claim in Paulignan, Jeannerod, et al., 1991).

Every time the size of the first target changed we found an increase in the duration of the movement, irrespectively of whether the target became smaller or bigger. This suggests that the slowing down of the movement was a general response to the change, and not an adaptation of the movement to the new properties of the target. This slowing down of the movement may be a strategy for dealing with unexpected visual information, much as we proposed for the overall increase in dwell time. It is important to point out that such reaction to a change occurs in a more selective manner than the changes in dwell time, because when the second target changed there was no increase in the duration of the movement towards the first target. On the other hand, the dwell time was shorter than the fastest possible reactions (unless the first target was small), so this difference is probably not due to a fundamental segregation of the two movements, but to a slower response to the change in the properties of the second target (during the first movement).

Our experiments suggest that the predictability of the direction of the change affects the movement kinematics. For many of the kinematic measures, we found significant differences between movements to identical pairs of targets in Experiments 1 and 3. When both the first and the second target could change (as in Experiment 3) subjects' movements were generally slower. This effect on the speed of the movement could be related to the need to monitor more changes, which would be consistent with both movements being considered as a whole, rather than as two separate components (but the effect could also be attributed to the different proportions of trials with a small first target). The fact that the dwell time increased after a change in either the first or the second target supports the view that the two movements are considered as one action. We also found significant differences in movement kinematics between Experiments 2 and 3. However, the temporal requirements of the task (the maximal movement time that was accepted without subjects being instructed to move faster) differed between these two experiments. Thus, we cannot tell whether the differences in kinematics were due to differences in the feedback, or to differences in the predictability of the changes. In contrast to the speed of the movement, the responses to changes did not differ between the experiments (no significant interactions between *manipulation* and *experiment*).

We conclude that our sequences of movements are treated as a single action, despite the fact that there is a clear intermittent target. Whether multiple movements are also considered as a single action when the movements in the sequence are less similar, as is the case for the movements that build up most of our daily actions, remains to be examined.

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