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Fast corrections of movements with a computer mouse

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Abstract—When we reach out for an object with our hand, we transform visual information about the object's position into muscle contractions that will bring our digits to that position. If we reach out with a tool the transformation is different, because the muscle contractions must bring the critical part of the tool to the object, rather than the digits. The difference between the motion of the hand and that of the tool can be quite large, as when moving a computer mouse across a table to bring a cursor to a position on a screen. We examined the responses to unpredictable visual perturbations during such movements. People responded about as quickly to changes in the position of the target when pointing with the mouse as when doing so with their hand. They also responded about as quickly when the cursor was displaced as when the target was displaced. We show that this is not because the visually perceived separation between target and cursor is transformed into a desired displacement of the hand. Our conclusion is that our actions are controlled by the judged positions of the end-effector and the target, even when the former is quite detached from the muscles and joints that are involved in the action.

Keywords: Motor control; tools; goal-directed movements; reaction time; pointing.

INTRODUCTION

In order to reach out for an object with our hand, we must transform visual information about positions that are suitable for grasping the object into muscle contractions that will bring our digits to those positions. The way in which this transformation takes place is still not clear.

One suggestion is that visually perceived ego-centric positions are transformed into postures that will bring the digits to the appropriate positions (e.g. Rosenbaum *et al.*, 1995). In support of this view it has been shown that goal-directed movements are possible without visual or proprioceptive information about the arm (e.g. Blouin *et al.*, 1993) and that errors in movement endpoints are distributed in a viewer-centred manner (e.g. McIntyre *et al.*, 1997) and do not necessarily depend on the starting position (van den Dobbelsteen *et al.*, 2001).

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An alternative suggestion is that the separation between the digit and the target position is transformed into a desired displacement. That would explain why errors can accumulate across sequential arm movements (Bock and Arnold, 1993). The separation could be determined on the basis of visual information alone, making use of the highest available spatial resolution (from sources such as binocular disparity), but it could also make use of the felt position of the hand (Graziano, 1999; Buneo *et al.*, 2002).

People probably use different kinds of information under different circumstances (Gentilucci *et al.*, 1997; Smeets *et al.*, 2002), which seems to make it a hopeless task to try to find a 'preferred' transformation. However, assuming that the 'preferred' transformation is the one that works fastest (Brenner and Smeets, 2001), we decided to specifically look at the fast corrections that guide one's hand to a target.

In order to be able to visually guide one's hand to a target, the time that it takes to process the visual information must be much shorter than the movement time. How quickly vision can influence a movement of the hand becomes evident when an object toward which we are moving our hand is suddenly displaced. In such cases we quickly and unconsciously correct the hand's path (Pisella *et al.*, 2000). We do not have to be able to see our hand or notice the displacement to make such corrections (Goodale *et al.*, 1986). Fast corrections to an invisible hand's path are even possible in the complete absence of proprioception, (Bard *et al.*, 1999). Thus such fast corrections can be based on converting visual information about the target's instantaneous egocentric position (Rossetti, 1998) into the muscle commands that will bring the hand to that position (Desmurget *et al.*, 1999).

If fast corrections are driven in this manner, it is not self-evident that they should also be possible when we are not moving our digits to the target, but the relevant part of a tool that we are holding in our hand. For the proposed mechanism to work when using tools, the relationship between the final position of the hand and that of the tool would have to be considered. For some tools, such as a computer mouse, this relationship is very complicated, because the position of the hand that is moving the mouse is only very indirectly related to the position of the cursor. Yet we seem to be quite proficient with this tool.

The fact that fast corrections can be made without vision of the hand (Pélisson *et al.*, 1986) means that they are possible without visual information about the separation between the hand and the target. However, this does not necessarily mean that they cannot be made on the basis of the visually perceived separation between the hand (or cursor) and the target if such information is more suitable under the prevailing conditions. Vision of the hand as it approaches the target is known to be critical for performing fast movements accurately (Carlton, 1981). Perhaps our proficiency with tools such as the computer mouse is therefore based on such information. In order to find out we conducted a series of simple experiments in which we examined whether fast corrections are possible when moving a cursor to a target on a screen and, if so, what visual information people use to do so.

EXPERIMENT 1

Methods

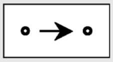
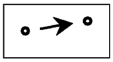
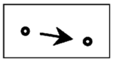
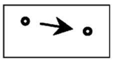
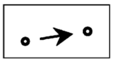
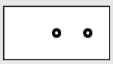
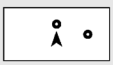
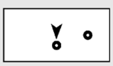
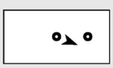
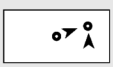
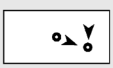
Stimuli were presented on a Sony G200 monitor (31 × 24 cm; 1024 × 768 pixels; 120 Hz) using an Apple G4 computer and a mechanical disk-shaped mouse (one with a ball). Subjects sat facing the screen and moved the mouse across a large uncluttered tabletop to quickly bring a cursor to a target. They were explicitly instructed to move the cursor to the targets as quickly as they could. They were free to place the mouse wherever they liked on the table. They usually held it slightly to one side, presumably because that was where they were used to having the mouse, and because this allowed them to comfortably make large movements of their lower arm. Subjects received no special training, but they were all experienced at using a computer mouse.

The cursor was a 12 mm diameter black disk with a 4 mm diameter green spot at its centre. The target was a similar disk with a red spot at its centre. The rest of the screen was white. Once the cursor touched the target the latter disappeared and a new target appeared 6 cm from the other side of the screen. It could appear at the horizontal midline or 1.5 cm higher or lower. On some trials on which the movement was between the two central positions, the *target* jumped 1.5 cm upwards or downwards as soon as the cursor passed the vertical midline. On some other such trials the *cursor* jumped 1.5 cm upwards or downwards at that moment. The different kinds of trials and the number of times each was presented are shown in Table 1.

Mouse coordinates were obtained at the frame rate of 120 Hz. The total horizontal displacement of the hand was only about 9 cm because the cursor moved about twice as fast as the mouse. In this paper we refer to a lateral mouse movement that normally moves the cursor horizontally across the screen as a horizontal movement, and a sagittal one that normally moves the cursor vertically as a vertical movement. The resolution was one pixel, corresponding with a displacement of the hand of about 0.15 mm, or a cursor displacement of 0.3 mm. The mouse coordinates were transformed into velocity signals by taking the differences between consecutive values and dividing them by the 8 ms interval between the frames. We only analysed the movements in which either the target or the cursor jumped vertically when the cursor crossed the screen centre. The jumps could occur when the cursor was moving to the left or to the right. However, since we were only interested in the vertical component of the movement, we ignored this distinction.

In order to make sure not to interpret systematic curvature of the cursor's path as a response, we averaged across trials with upward and downward jumps after changing the sign of the velocity for downward jumps. Thus the velocity was always considered positive if it was in the same direction as the jump. Averaging across upward and downward jumps gave us 100 trials per session for each kind of perturbation. Twenty-three people took part in the first experiment, of whom seven did so twice, giving a total of 30 sessions.

Table 1.
The conditions in the 3 experiments. On half of the trials the target is on the right and the cursor starts on the left (as shown), and on the other half the target is on the left and the cursor starts on the right. In the third experiment the target jumps when the cursor is at one third of the screen (not the centre) and on 200 of the 300 trials the cursor is invisible when the target jumps. When the previous target was high or low the cursor started higher or lower, so that separate trials were needed to return the cursor to the midline

	condition	number of trials in experiment		
		1	2	3
	target on midline	300	600	400
	target above midline	50	50	50
	target below midline	50	50	50
	previous target was high	100	200	200
	previous target was low	100	200	200
When targt on midline and cursor crosses screen centre . . .				
	nothing special happens	100	100	100
	target jumps upwards	50	50	150
	target jumps downwards	50	50	150
	cursor jumps upwards	50	50	
	cursor jumps downwards	50	50	
	both jump upwards		50	
	both jump downwards		50	
	cursor changes direction (deviates upwards)		50	
	cursor changes direction (deviates downwards)		50	
	target jumps up and cursor deviates upwards		50	
	target jumps down and cursor deviates downwards		50	

Results and discussion

Figure 1 shows the response to each kind of perturbation during each of the 30 sessions. The vertical axis shows the average vertical velocity of the mouse. The horizontal axis shows the time relative to the moment that the jump was visible on the screen. The velocity signal was based on two samples, so we considered it to relate to the time midway between the two samples. The thin grey lines show the average responses during individual sessions. The thick black lines show the overall average. The responses to target jumps and to cursor jumps are in opposite directions because the appropriate response to an upward jump of the target is upwards, whereas the appropriate response to an upward jump of the cursor is downwards.

The median time from the moment that the new target appeared until the cursor passed the screen centre was 325 ms. The median time that it took for the cursor to cover the remaining horizontal distance to the target was 175 ms on unperturbed trials and 192 ms on perturbed trials. The main difference in timing between perturbed and unperturbed trials is that subjects usually initially missed the target on perturbed trials. Thus, the median time between the cursor first reaching the horizontal position of the target and it reaching the target itself was 117 ms on perturbed trials (and zero on unperturbed ones).

It is evident from Fig. 1 that people respond quickly to both kinds of jumps. The latency of the responses was between about 100 and 150 ms. This is comparable to the latency that was found when reaching with the hand (fastest response estimated to be after 115 ms; Prablanc and Martin, 1992) or hitting with a hand-held rod (fastest response after 110 ms; Brenner and Smeets, 1997). Thus fast responses are possible when the visual target is physically displaced from the position toward

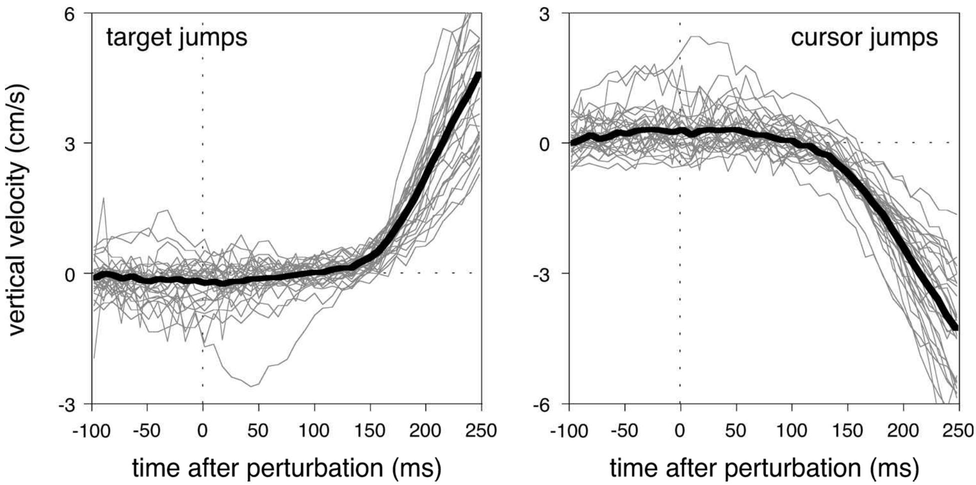


Figure 1. Average responses of individual subjects (thin grey lines) and overall average responses (thick black lines) to each of the two kinds of perturbation in the first experiment.

which the hand is moving, and even when it is the visual representation of the position of the hand that is displaced.

We suggested in the Introduction that subjects might use the visually perceived separation between the cursor and the target in tasks such as ours. That would explain the fast responses that we found for our cursor jumps. However, the responses to cursor jumps appear to be slightly faster than responses to target jumps, which is inconsistent with this suggestion. To test whether responses are really faster for cursor jumps than for target jumps we determined (for each of these perturbations) when the average response on each session reached a threshold velocity of 1 cm/s. A paired t-test on these latencies confirmed that the mean difference of 14 ms was significant ($p < 0.0001$).

Before concluding that subjects were not using the visually perceived separation to perform our task we have to consider other possible reasons for a faster response to cursor movements. One possibility is that for some reason the neuronal delays for detecting the cursor's position are shorter than those for detecting the target's position, so that the separation is determined between positions that are present at different times. The cursor and target were physically almost identical, but the cursor is expected to change its position, while the target is not, which may somehow influence the processing speed. Another possibility is that it is not the perceived separation that guides the hand, but the relationship between the perceived position of the target and the perceived direction of cursor motion. The two changes may therefore not be completely equivalent. In our second experiment we attempt to distinguish between such possibilities.

EXPERIMENT 2

Methods

The methods were identical to those of the first experiment except that we added three new conditions (see Table 1). In one new condition both the cursor and the target jumped together, so that their relative positions did not change. In the other two new conditions, the cursor did not jump but changed its direction of motion by 9 degrees. This change in direction corresponds to a vertical displacement of the cursor of 1.5 cm during the remaining horizontal distance of 9.5 cm to the target. In one of these new conditions the target did not move. In the other it jumped 1.5 cm (as in the original condition in which the target jumped), so that it was at the position that the change in direction was now leading the cursor. Sixteen people took part in the experiment, which was split into two sessions because of the increased number of movements.

Results and discussion

Figure 2 shows the overall average performance in all five conditions (together with the overall average performance for the two conditions of the first experiment). For clarity, only the interval between 100 and 200 ms after the perturbation is shown. Performance in the two original conditions was very similar to that in the first experiment. In both experiments, responses to target jumps (*top two thick traces*) were slightly slower than responses to cursor jumps (*lowest two thin traces*). In the second experiment the average difference was 21 ms ($p = 0.003$).

When both the target and the cursor jumped together, so that their relative positions did not change, and therefore no change in movement was required, there was a small but evident response (*central solid black trace*). This response was very similar to the sum of the responses to independent target and cursor jumps (*dashed black trace*). The response to a change in the direction in which the cursor moves (in relation to the movement of the mouse) took slightly longer to initiate and was less vigorous than the response when the cursor jumped (*thin grey trace*). This pattern is

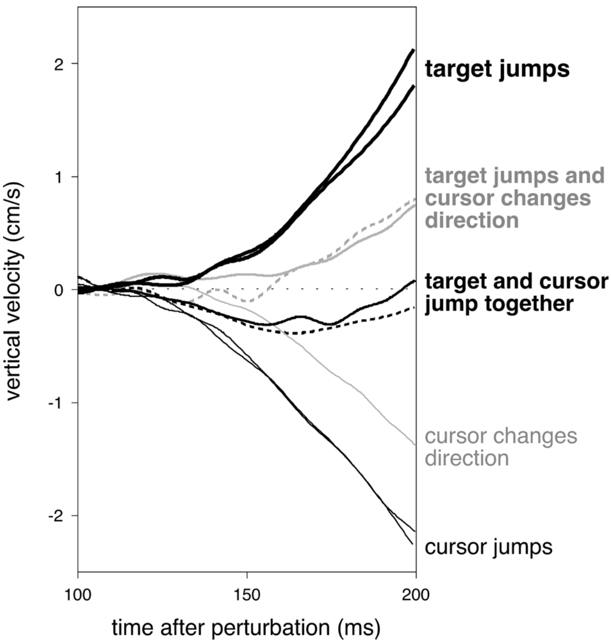


Figure 2. Overall average response to each kind of perturbation in the first and second experiments. The two thick black curves at the top are for target jumps (one for each experiment). The two thin black curves at the bottom are for cursor jumps. The fifth solid black curve is for the target and cursor jumping simultaneously in the same direction. The thin grey curve is for a change in the direction in which the cursor moves. The thicker solid grey curve is for the same change in direction of cursor motion when the target jumps in the same direction. The two dashed curves show what one predicts for the combined perturbations of target and cursor if such responses are the sums of the responses to the two perturbations on their own.

consistent with the influence that the change in direction has on the cursor's vertical position: on average the cursor reached 10% of the amplitude of the jump in 8 ms, and 50% in 53 ms. When the change in cursor direction was accompanied by a target jump, so that again there was no need to adjust the movement of the mouse, the response (*thick grey solid trace*) was again close to the sum of the responses to the two separate perturbations (*thick grey dashed trace*).

The median time that it took for the cursor to reach the screen centre was 317 ms. The median time that it took for the cursor to cover the remaining horizontal distance to the target was 158 ms (irrespective of whether there was a perturbation or not). The median time between the cursor first reaching the horizontal position of the target and it reaching the target itself was 42 ms on perturbed trials (and zero on unperturbed ones). The fact that subjects hit perturbed targets sooner in the second experiment than in the first is probably largely due to the fact that no response was required on many of the perturbed trials in the second experiment.

Apart from replicating the findings of the first experiment, the second experiment demonstrates that responses to both the target and cursor jumping simultaneously are equivalent to the sum of the responses to each on its own. Thus the responses to the two perturbations appear to be independent. Similar results were found when the cursor did not jump to a new position but changed its direction of motion (with respect to that of the mouse). The response to a combination of a target jump and a change in cursor direction is still increasing long after the response to both the target and the cursor jumping has stopped doing. This confirms that subjects rely on the cursor's position rather than its direction of motion. The smaller response to a target jump when accompanied by a change in cursor direction shows that subjects do not simply respond maximally when they detect a change in relative position.

The second experiment supports our impression that people do not directly use visual information about the relative positions of target and cursor to guide their actions. We had expected people to use such information when working with a computer mouse, because the relationship between the person's posture and the visually perceived position of the end-effector (the cursor) are disrupted by this tool. The transformation that is required to use a computer mouse is not simply a shift in coordinates, because the cursor moves twice as fast as the hand does and moves upwards when the hand moves forwards. Moreover, the relationship between the position of the hand and that of the cursor changes during the experiment. Even the relationship between the direction in which the mouse moves and the direction in which the cursor moves is not completely fixed, because it depends on the orientation of the mouse. However, the transformation is not arbitrary either. For some reason this particular transformation is exceptionally easy to deal with, as is evident if we try to work with the mouse turned by 90 degrees. Thus finding out what information is used for fast corrections in this particular task may help us determine the 'preferred' transformation for controlling ones movements.

EXPERIMENT 3

Methods

We could still not completely dismiss the possibility of there being timing differences between the processing of visual information about the cursor and the target, or the possibility that a combination of their perceived separation and the direction of cursor movement is used. To make sure that we were not misinterpreting our data we repeated the target-jump part of the first experiment with two small changes. The main change was that on some trials the cursor was not visible when the target jumped. The second change was that the target jumped when the cursor reached one-third of the screen width, rather than the midline. Otherwise the methods were identical to those of the target jump condition of the first experiment (see Table 1).

The insets in Fig. 3 give an impression of the position of the cursor at which the target jumped (*dashed line*) and the range of positions for which the cursor was invisible (*shaded areas*). These are shown for movements to the right. The target jumped when the cursor was 10 cm from the left edge of the screen. In two of the three conditions the cursor was not visible at this time, because it had disappeared once it was 9 cm from the left edge. In one of these conditions the cursor reappeared when it crossed the screen centre. In the other it only reappeared when it was 10 cm from the other edge. Of course, all the distances are from the opposite edge for movements to the left. Twelve people each took part in a single session of 900 movements.

Results and discussion

Figure 3 shows the average responses to a target jump when the cursor remained visible and when it disappeared about 42 ms before the jump, only to reappear either 100 ms or 167 ms later. Note that these times are median values. The actual timing of the disappearance and reappearance of the cursor depended on the horizontal speed of the cursor on that particular trial. The responses to the target jump may be slightly attenuated when the cursor is invisible, but the timing is not affected.

If the responses had been based on the visually perceived separation between the cursor and the target, we would have expected them to be delayed until 100–150 ms after the target reappeared. They were not. Thus the third experiment again confirms our impression that the fast responses are not based on changes in the visually perceived separation between target and cursor. These findings do not prove that people cannot use visually perceived separations to guide their movements. However, they show that the fastest responses are not based on such information, suggesting that this is not the primary way in which movements are controlled.

If people do not rely on visual information about relative positions to guide their movements, they must localise the cursor relative to some other frame of reference. In contrast to the hand, which we can feel when it is not visible, the cursor's position cannot really be known when it is not visible. How then is it possible that people can control the invisible cursor? A recent study (Yamamoto and Kitazawa, 2001)

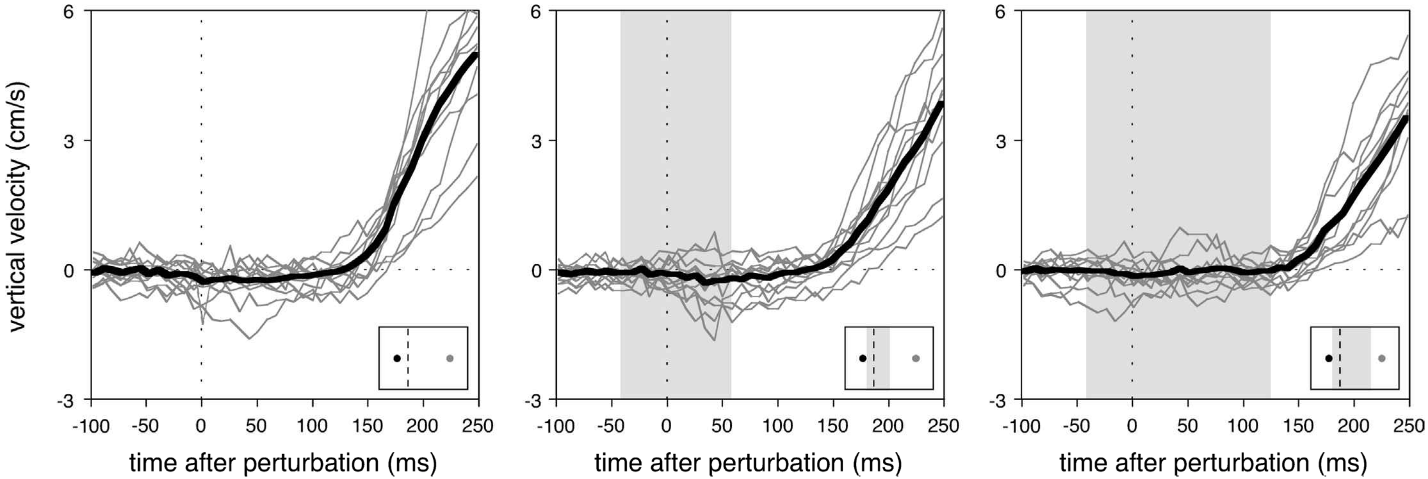


Figure 3. Average responses to target jumps in the third experiment. The shaded portions in the main panels show the median time during which the cursor was invisible. The timing of the response was independent of whether the cursor was visible.

has shown that people readily shift their judgements of felt position to the tip of a physical tool (a stick). Perhaps people do so for virtual tools (such as the cursor) as well. However, this is not enough to explain how our subjects were able to respond to the target jump when the cursor was invisible. For this, subjects must not only '*feel*' the cursor at the position at which they have just seen it, but they must also update this felt position on the basis of the movement of the hand. They must be able to do so even though the cursor moves at a different rate and in a different direction than the hand. We are still far from understanding how this could be achieved. However, such a mechanism would provide extreme flexibility in choosing an end-effector for a task, and would therefore explain why we can so easily perform a learned action with different parts of the body (Merton, 1972) and with all sorts of tools.

CONCLUSION

If people do not directly use the visually perceived separation between the end-effector and the target to guide their movements, they must start with a judgement of the target's position in a frame of reference that can be related to the position of the end-effector. The final stage in controlling the movement is obviously determining how the muscles must contract in order to achieve the required change in posture. It is enticing to assume that a visually perceived ego-centric position is directly transformed into a desired posture (Feldman and Levin, 1995; Rosenbaum *et al.*, 1995). The fact that we can respond so quickly with the computer mouse, and in particular that we can do so when it is the cursor that is displaced, shows that this is not the way our movements are controlled. Instead we appear to use a control strategy that can incorporate complex transformations without this introducing substantial delays.

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