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RESEARCH ARTICLE

Avoiding moving obstacles

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Abstract To successfully move our hand to a target, we must consider how to get there without hitting surrounding objects. In a dynamic environment this involves being able to respond quickly when our relationship with surrounding objects changes. People adjust their hand movements with a latency of about 120 ms when the visually perceived position of their hand or of the target suddenly changes. It is not known whether people can react as quickly when the position of an obstacle changes. Here we show that quick responses of the hand to changes in obstacle position are possible, but that these responses are direct reactions to the motion in the surrounding. True adjustments to the changed position of the obstacle appeared at much longer latencies (about 200 ms). This is even so when the possible change is predictable. Apparently, our brain uses certain information exceptionally quickly for guiding our movements, at the expense of not always responding adequately. For reaching a target that changes position, one must at some time move in the same direction as the target did. For avoiding obstacles that change position, moving in the same direction as the obstacle is not always an adequate response, not only because it may be easier to avoid the obstacle by moving the other way, but also because one wants to hit the target after passing the obstacle. Perhaps subjects nevertheless quickly respond in the direction of motion because this helps avoid collisions when pressed for time.

Keywords Human arm movements · Visual control · Perturbations · Fast responses · Obstacles

Introduction

In daily life, hand movements often have to be performed in cluttered environments. For example, imagine yourself reaching out for your pen between the books, papers and cups lying on your table. To adequately control the way that you reach for the pen you must ensure that your hand does not collide with the other objects. Surprisingly, although we normally perform successful movements under such circumstances, little is known about how obstacles influence the way that we control our hand movements.

In most studies of human hand movements the target of the movement was presented in isolation. Several such studies have shown that visual information is used during the execution of a movement to correct errors in the hand's path. When the target of the movement is displaced, the minimal amount of time needed to start correcting the on-going hand movement is about 120 ms (Brenner and Smeets 1997, 2003b; Day and Lyon 2000; Prablanc and Martin 1992; Smeets et al. 1998; Soechting and Lacquaniti 1983). However, responses are not always that fast: reaction times of around 200 ms or longer have also been found for similar manipulations (Day and Lyon 2000; van

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Sonderen et al. 1988). The time needed to respond to a change in position seems to depend on various aspects of the task, like the direction of the change (Elliott et al. 1995; Paulignan et al. 1991), the predictability of the displacement (Boulinguez and Nougier 1999), and the visual information that defines the target (Veerman et al. 2008). Nevertheless, taken together, all these results suggest that in simple situations we are able to respond quite quickly to new visual information about the target.

From the few studies in which there were other objects near the target it is known that the presence of obstacles influences various temporal and spatial aspects of the movement of the hand. In grasping tasks, for example, the duration of the hand movement normally increases when obstacles are present, compared to the same movement executed without obstacles (Biegstraaten et al. 2003; Jackson et al. 1995; Jaric et al. 1999; Mon-Williams and McIntosh 2000; Mon-Williams et al. 2001; Saling et al. 1998; Tresilian 1998). Maximum grip aperture also decreases when the grasping movement is executed in the presence of obstacles (Jackson et al. 1995; Mon-Williams et al. 2001; Saling et al. 1998; Tresilian 1998). When pointing, obstacles influence the hand's path in a manner that depends on the location and orientation of the obstacle, as well as on the direction of the movement (Brenner and Smeets 2007; Dean and Brüwer 1994; Sabes and Jordan 1997). People generally try to make sure that their hand does not come closer to the obstacle than some minimal distance (Dean and Brüwer 1994; Tresilian 1998). The presence of obstacles also has an effect on the eye movements that accompany the hand's movement. For example, in a task in which subjects had to move a bar to a target location without hitting an obstacle, Johansson and colleagues found that the obstacle was fixated on 80% of the trials, and that it was hit more often when eye movements were not permitted (Johansson et al. 2001). Even objects that are completely irrelevant to the movement (*distracters*) can influence hand movements (Gangitano et al. 1998; Howard and Tipper 1997; Jackson et al. 1995; Kritikos et al. 2000; Meegan and Tipper 1998; Mon-Williams et al. 2001; Pratt and Abrams 1994; Saling et al. 1998; Tipper et al. 1997). All these results suggest that other objects besides the target are also considered during movement preparation and execution.

Until now the studies that analyzed how the presence of other objects than the target of the movement affects hand movement control have used static environments. However, most of our movements occur in environments with other actors, who also interact with the environment. Therefore, objects may suddenly appear or they may move to a new position. What happens when other objects than the target shift position unexpectedly during the execution of a movement? Can we correct our movement accordingly? It is known that people respond about as quickly when the visually perceived position of their hand (Saunders and Knill 2003) or of a tool that is guided by their hand (Brenner and Smeets 2003a) suddenly changes position, as when the target of their movement suddenly does so. If obstacles are considered to be as relevant for the movement as the target or the hand, we could expect similarly fast responses to a displacement of an obstacle. Results from studies in walking show that people can indeed respond very quickly to the sudden appearance of an obstacle in front of their foot (Weerdesteyn et al. 2004). However, this does not necessarily need to be the case for goal-directed hand movements, as there is a crucial difference between the two kinds of tasks. In walking the target of the foot's movement is not explicitly defined, so subjects can just change the "target" of that step to avoid the obstacle. When performing goal-directed hand movements there is a clearly defined target for the hand, so the obstacle needs to be avoided without changing the fact that reaching the target is the goal of the movement. This distinction raises an interesting question: do the fast mechanisms for the on-line control of movements only consider the interaction between the actor and the target, or is the whole environment considered? In particular, are potential obstacles considered?

In the present study we examine whether the hand's movements are quickly adjusted when the positions of obstacles on its path towards a target change without the endpoint of the movement changing. Subjects were asked to perform fast hand movements from a starting position on the right to a target on the left, while avoiding either one or a pair of "virtual" obstacles.[1] Obstacles were presented simultaneously with the target shortly after the subject's hand was at the starting position. Occasionally either the target or the obstacle (or pair of obstacles) was displaced, just after the movement had started. By recording the hand's movements with a graphic tablet, and comparing different directions of displacement, we were able to estimate the amount of time needed to respond to the displacement of the obstacles. Different combinations of obstacle positions and kinds of displacement were presented to try to identify the visual information that is used for the corrections.

Experiment 1

The first experiment was designed to examine whether responses to a displacement of an obstacle are as quick as

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[1] Although these items did not really obstruct the movement, subjects were instructed not to hit them and received feedback if they nevertheless did so, so we find it more appropriate to consider them as obstacles than as distracters.

those to the displacement of a target. As discussed in the previous section, little is known about how people react to sudden changes in the position of other objects in the environment than the target. Therefore, the main purpose of this first experiment was to compare the speed of responses to displacements of a target and an obstacle.

To force subjects to avoid an obstacle by moving approximately along a specific path, rather than for instance by moving on a very curved path to reach the target from a different direction, we presented two large obstacles with an opening between them. Participants were informed that the target should be reached by passing through the opening. The opening was initially aligned with the target. Occasionally the obstacles changed position (simultaneously and in the same direction), creating the impression that the opening had moved (see upper panel in Fig. 1). On some other trials the target was displaced by a similar amount.

Methods

Participants

The three authors and seven of our colleagues who had previous experience with similar tasks, but were unaware of the purpose of the present study, took part in the experiment (6 males and 4 females; ages ranging from 25 to 48). All participants had normal or corrected to normal vision and had no known neuromuscular deficits at the moment the experiment was run. All participants, except one, reported to be right-handed. The left-handed subject performed the task with an inverted version of the stimuli (left to right movement) to ensure that his moving hand did not occlude the target and obstacles. All participants gave their informed consent to participate in the experiment. This study was part of an ongoing research project that was approved by the local ethics committee.

Procedure

Participants sat comfortably in a chair in front of a graphic tablet (Wacom A2), holding a stylus in their dominant hand. The tablet recorded the two-dimensional position of the stylus at a frequency of 200 Hz. We will refer to these positions as the position of the hand. A semi-transparent mirror setup was used to present the stimuli so that they appeared to be on the surface of the tablet while the participant could clearly see his or her hand. The resolution of the display was 1,024×768 pixels, with each pixel corresponding to approximately 0.5 mm on the surface of the tablet. The target was a white, 4 cm long rectangle that was 30 cm to the left of the starting position. The obstacles were red rectangles, 25 cm to the left of the starting position. Both were oriented perpendicular to a straight path to the target. In the first experiment we had two large obstacles (each almost 20 cm long) with a 4 cm opening between them (see upper panel in Fig. 1). The opening was always initially aligned with the target. The target and

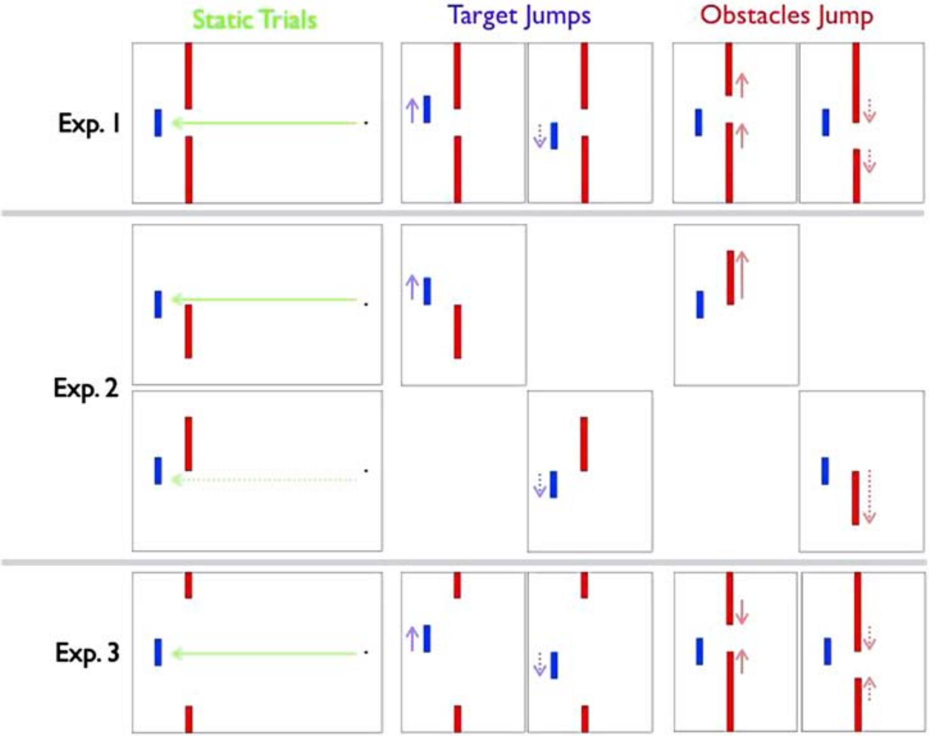

Fig. 1 Possible positions of the white target (shown here in *blue*) and of the red obstacle(s) in the three experiments. When either the target or obstacle(s) jumped the initial configuration (as in *static trials*) abruptly changed into one of the other four configurations (*target jumps* or *obstacles jump*). *Blue* and *red arrows* indicate the perceived direction of motion for the target and obstacle respectively, with *continuous* and *dotted lines* indicating the two directions of motion

obstacles were *static* on 40% of the trials. In the remaining trials either the *target jumped* 2 cm, or the *obstacles jumped* to new positions creating the impression that the opening had moved 2 cm (see upper panel in Fig. 1). The target and obstacles jumped on 30% of the trials each. These jumps occurred 350 ms after the stimulus was presented, and were always perpendicular to the main direction of the movement (half in each direction). Trials of the five different conditions were presented in random order.

The task was to slide the stylus from right to left across the tablet so that it passed through the target while avoiding the obstacles. At the beginning of each trial a small dot (*starting position*) was presented on the right side of the screen (or the left side for the left-handed participant). Subjects had to place the stylus steady on the starting position for the trial to start. The target and obstacles appeared simultaneously, soon after the stylus was placed at the starting position. This was the signal to begin the movement. On some trials either the target or the obstacles changed position 350 ms later. On most trials the hand was already moving by then (if the movement had not started within 350 ms the trial was eliminated). Trials ended once the stylus reached a position located further than 30 cm to the left of the starting position (or to the right for the left-handed subject), independent of whether the stylus passed through the target or not.

Subjects were instructed to perform fast movements that reached the target while avoiding the obstacles. Both aspects of the task were presented as being equally relevant. Each trial consisted of one hand movement from the starting position to the target. The hand, target and obstacles were continuously visible during the movement. The position of the stylus on the graphic tablet was recorded at a frequency of 200 Hz. After each trial feedback was presented in the form of a message on the screen if the subject hit an obstacle, missed the target, or took more than 800 ms (from target presentation) to finish the movement. Each subject performed a total of 200 trials, in two sessions of 100 trials each. Sessions lasted about 20 min.

Data analysis

Only trials in which the manipulation occurred after movement initiation were included in the analysis. We also checked the quality of the recordings and discarded any trials in which there were technical problems (e.g. if the subject accidentally lifted the pen off the surface of the tablet, or if the movements were performed very fast, in which case the tablet often failed to record the stylus' position). Altogether, 25% of the trials were eliminated for these reasons (including all of the trials of one subject). The remaining trials were included in the analysis, regardless of whether the obstacle was hit or not. Table 1 shows the total number of trials considered in the analysis for each of the participants in the experiment.

Movement trajectories were calculated from the *x*–*y* positions recorded with the tablet. Tangential as well as lateral and sagittal velocities were calculated by dividing the distance between consecutive samples by the 5 ms sampling interval. Because the noise in the recordings was very low, no filtering or smoothing algorithms were

Table 1 Individual results in experiment 1

	Leftward velocity	Response to target (ms)	Response to obstacle (ms)	Obstacle hits	Target missed	Valid trials
S.1	7.2	155	165	24 (40%)	0 (0%)	195
S.2	8.7	140	200	15 (37.5%)	7 (14.5%)	151
S.3	11.1	150	245	23 (45%)	14 (24.5%)	177
S.4	12.1	145	160	18 (40.4%)	8 (18.4%)	131
S.5	9.5	135	145	21 (39.5%)	8 (10.9%)	171
S.6	7.5	170	185	13 (22.8%)	2 (3.7%)	179
S.7	11.3	120	–	25 (47.9%)	6 (13.3%)	155
S.8	8.1	155	190	20 (39.2%)	0 (0%)	177
S.9	7.2	170	150	14 (27.4%)	3 (5.6%)	173
X	**9.2**	**149**	**180**	**19.2 (37.7%)**	**5.3 (10.1%)**	**168**

The first column indicates the participant, referred to by the same number across all tables. The second column shows the average leftward velocity (calculated from the point at which the velocity of the hand is higher than 2 cm/s until the hand hits or passes the target) over all trials and conditions, in cm/s. The third and fourth columns show the latencies of the responses to target and obstacle motion: the first point in time at which the difference between the two directions of motion reached significance (see text for more details; no value is given if the difference is never significant). The fifth and sixth columns report the number of times that the subject hit the obstacle and missed the target (and the percentage of trials on which the item in question was manipulated in which this was the case). The last column reports the total number of trials considered for the analysis (from a total of 200). On average, participants hit less than 1% of the obstacles and missed less than 1% of the targets when neither moved. Participants twice hit an obstacle when the target jumped, and never missed the target when the obstacles jumped. Subject S.9 is left-handed, so the second column reports the rightward velocity applied, except for a simple algorithm for interpolating occasional single missing data points. The advantage of not filtering the data is that the original temporal resolution of the measurement is not compromised by the temporal blur caused by applying a filter. Since the results will show that the analysis of our experiments yields results that are reproducible across subjects, we consider that the noise level in the unfiltered velocity traces is acceptable.

As discussed above, the main purpose of this experiment was to compare subjects' responses to the displacements of the target and the obstacles. Since participants were required to correct their trajectories in response to both these displacements, we expected to find differences in the velocity profiles between the five conditions and decided to use the point at which the velocity profiles started to diverge as a measure of the response time. From an examination of the lateral, tangential and sagittal velocity traces for each condition it became clear that there was very little, if any, response in the lateral and tangential directions. We therefore estimated when the first response to the target and obstacle jumps occurred by comparing the sagittal velocity traces. That the most evident differences are in this direction is quite logical because subjects had to move their hand in the sagittal direction to adjust the trajectory to the various manipulations of the target and the obstacles. As the main movement of the hand was in a lateral direction and the displacements of the target and obstacles were in the sagittal direction, the sagittal velocity component is quite a pure measure of the correction.

Our main interest was in the difference in latency between the responses to the target jump and those to the obstacle jump. It is possible to obtain a first estimate of the response latency by looking at the average traces. For each condition and every 5 ms from the moment of the change, the sagittal velocity was averaged across trials for each subject, and then across subjects. The point at which the average traces start to diverge can be considered to be the time of the very first response. To obtain separate estimates of the latency of the different responses for each subject we used one-tailed *t* tests to compare the velocity on trials in which the jumps were in opposite directions, again for every 5 ms from the moment of the change. The two conditions in which the target jumped were compared to estimate the latency of the response to the target's displacement. An equivalent comparison was done for the obstacle. Since this procedure involves running many *t* tests, we had to somehow deal with such repeated testing. We could not apply any of the usual corrections because our measures are clearly not independent. One way to deal with this is by reducing the number of comparisons. We did so by only considering reasonable times. Based on the literature discussed in the introduction we only considered times that were at least 100 ms after the manipulation. In most cases, it was then possible to find a point in time at which the comparison between the conditions changed from not being significant to being significant. However, occasionally we found significant differences between the traces at single points in time. To make sure that we did not base our estimate of the latency on such points that clearly cannot represent true responses, we only considered responses if the next two data points also reached significance. This method gives us the moment at which we are reasonably sure that a response has occurred, for each subject individually. It allows us to compare the response latencies for target and obstacle displacements within individual subjects and also to evaluate the consistency of the effects across subjects.

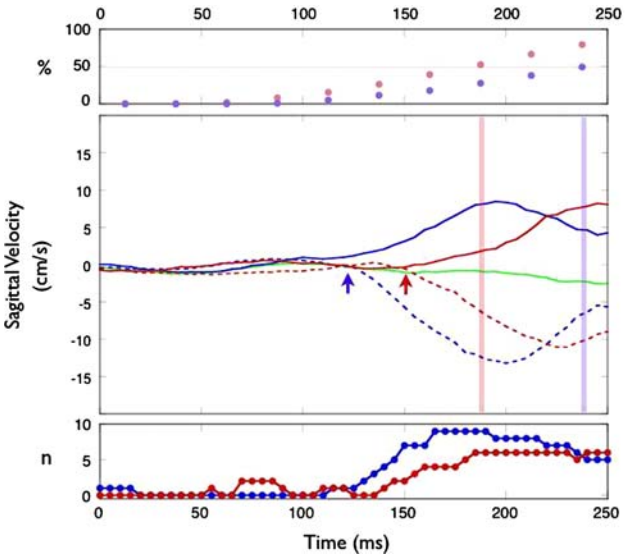

Fig. 2 Results of experiment 1. Time is measured from the moment at which the target or obstacles could jump to a new position. *Green* no jump. *Blue* target jumps. *Red* obstacles jump. *Continuous* and *dotted lines* represent the two directions of the displacements. *Central panel* average signed velocity of the hand in the direction orthogonal to the main direction of motion. *Arrows* indicate our visual estimate of the latency of the response. *Bottom panel* number of subjects for whom the hand's velocity was significantly different for the two directions of the displacement. *Top panel* percentage of trials in which the hand has reached the obstacle or target. The moment at which the hand had done so on 50% of the trials is also indicated by the *thick vertical lines* in the *central panel*

Results

The central part of Fig. 2 shows the average velocity in the sagittal direction for each of the conditions. Each line represents a different condition: static trials are shown in green, trials in which the target jumps are shown in blue, and trials in which the obstacles jump are shown in red. Continuous lines and dotted lines represent upward and downward displacements, respectively. All traces were aligned at the moment that the manipulation occurred (time 0 in the plot). By visually defining the point at which the lines of the different conditions separate we obtained a first estimate of the time needed to respond to the manipulation. According to this estimate, the first response to a change in the position of the target occurs about 120 ms after the change (blue arrow). This value is similar to the results obtained in earlier studies. A similar estimate for the change in obstacle position suggests that it took subjects about 150 ms to respond to the change in the position of the obstacles (red arrow).

Beside these overall estimates, one-tailed *t* tests were used to evaluate when reliable differences between the velocity traces arise for each of the subjects independently. The values obtained for responses to displacements of both the target and the obstacles are presented in Table 1. The bottom part of Fig. 2 shows the number of subjects for whom the hand's velocity was significantly different for the two directions of the jump at that point in time. As can be seen, both in Table 1 and in Fig. 2 (blue line), the earliest response, shown by one of our fastest subjects, occurs 120 ms after the manipulation. From that point in time the number of subjects who show a significant difference between both velocity traces steadily increases, and by 170 ms after the change in target position all subjects show a significant difference (i.e. they had all responded to the target jump). The average latency was about 150 ms. For the obstacle (red line in Fig. 2), the earliest response occurs 145 ms after the manipulation (see Table 1). The increase is more gradual than for the target jumps and does not include all subjects: our fastest subject did not show a response to the obstacle, probably because the target had already been reached by the time the response would have occurred (as will be explained below). The average latency of the subjects for whom we could determine a latency was 180 ms. In summary, both our estimates of the onset of the response show that subjects need about 25–30 ms longer to respond to changes in the obstacles' positions than to changes in the target's position.

The longer latency of responses to displacements of the obstacles means that responses to the obstacles will sometimes have been missed because they occurred too late. In the upper panel of Fig. 2 we show the percentage of trials on which the hand had reached the positions of the obstacles (light red) and the target (light blue) at each moment in time. The thick vertical lines in the central panel indicate the moments at which the hand had done so on 50% of the trials. At the moment at which most people had started responding to the obstacles having jumped, the hand had already passed the obstacles on 50% of the trials, so the response cannot have been very effective. That the response was indeed not very effective for avoiding the obstacles is evident from the fact that, on average, subjects hit an obstacle on 38% of the trials in which the obstacles jumped. They only missed 10% of the targets that jumped. However, there were big differences between subjects in the proportion of obstacle hits and target misses, as can be seen in Table 1. We found that the proportion of targets that were missed when they jumped was correlated with the speed of the movement ($r = 0.86$, $P = 0.005$). The proportion of times that obstacles were hit when they jumped was less clearly related to the speed of the movement ($r = 0.61$, $P = 0.10$).

Discussion

In this first experiment we analyzed subject's responses to a sudden change in the position of a pair of obstacles. We presented two large obstacles with an opening between them. The target had to be reached by passing through the opening. The opening was initially aligned with the target. In some trials, either the position of the target or the position of the obstacles changed. Subjects responded to both kinds of displacements.

Most subjects took longer to respond to a displacement of the obstacles than to a displacement of the target, despite the fact that the hand passed the obstacles before reaching the target, and despite the fact that the opening between the obstacles was the same size as the target, and that the magnitude of the displacement was also identical. However, the difference was not extreme and could at least partly be because the constraints for passing through the opening were not completely equivalent to those for hitting the target: subjects did not have to consider what would happen after passing the target, but they had to hit the target after passing the obstacles. Moreover, if subjects timed their hand movements to have enough time to respond to the obstacles' displacement, they would also have enough time to respond to the target displacement, but the opposite is not true. This may account for the different correlations between movement speed and performance that appeared in the experiment.

The fastest response to a target jump that we found occurred 120 ms after the displacement, which is similar to the results of previous experiments (Brenner and Smeets 1997, 2003a, b; Day and Lyon 2000; Prablanc and Martin 1992; Smeets et al. 1998; Soechting and Lacquaniti 1983). Interestingly, the first response to the obstacles jumping took only slightly longer: about 150 ms. Thus some people seem to make appropriate corrections to their hands' paths in response to changes in obstacle positions almost as quickly as they react to changes in the position of the target of the movement. This result suggests that obstacles are monitored during movement execution in almost the same way as targets are.

However, there is an alternative explanation that could account for our results. It is known that when irrelevant structures in the surrounding move, they ‘pull’ the hand in their direction of motion (Brenner and Smeets 1997; Saijo et al. 2005; Whitney et al. 2003). Perhaps this occurs because the retinal motion signals are interpreted as the consequence of oneself having moved. Such responses also have a latency that is slightly longer than that to a target moving at the same speed (Brenner and Smeets 1997). It is therefore possible that the fast responses to obstacles in this experiment were the result of a direct response to the obstacles’ motion, rather than a real adjustment of the hand’s path to the new position of the obstacles. To examine whether this was the case we performed a second experiment.

Experiment 2

To determine whether the fast responses to the changes in obstacle position that we found in the first experiment were based on information about the changed positions, or were a direct response to the retinal motion, we designed our second experiment so that the appropriate correction was in the opposite direction than the obstacle’s displacement. A single large obstacle was presented. It was at either of the two sides of a straight path to the target, and on some trials it switched to the other possible location (see the two central panels in Fig. 1). The only way to avoid colliding with the obstacle was to move in the *opposite* direction than the obstacle had appeared to move. Thus in this experiment we can distinguish between responses based on the changed obstacle positions, which would be in the opposite direction than the obstacle’s displacement, and responses based on the retinal motion, which would be in the same direction as the displacement.

Methods

Participants and procedure

The subjects, task and experimental procedure were similar to those used in the first experiment, with the following exceptions: three naive subjects, including the left-handed subject, were replaced, resulting in a population of seven male and three female right-handed subjects, with ages ranging from 25 to 48. Instead of two obstacles, we presented a single 8-cm long obstacle that was aligned with the center of the target (see central panels in Fig. 1). When it jumped it moved to the other possible position (so that the other end was aligned with the center of the target). Thus the direction in which the obstacle could move depended on its initial position. To avoid the obstacle after it jumped, subjects had to move their hand in the opposite direction. As in the first experiment, the target and obstacle were *static* on 40% of the trials. In the remaining trials either the *target jumped* 2 cm or the *obstacle jumped* to the other possible position (each on 30% of the trials). Trials of the different conditions were presented in random order. Each subject performed a total of 200 trials in a single session that lasted about 45 min.

Data analysis

The data were analyzed in the same way as in the first experiment. A total of 15% of the trials were discarded for technical reasons or because the manipulation occurred before the hand started to move. Table 2 shows the total number of trials considered in the analysis for each of the participants in the experiment. As in the first experiment,

Table 2 Individual results in experiment 2

	Leftward velocity	Response to target (ms)	Response to obstacle motion (ms)	Response to obstacle position (ms)	Obstacle hits	Target missed	Valid trials
S.1	6.3	160	130	200	18 (30%)	0 (0%)	192
S.2	8.1	105	180	240	38 (90.4%)	1 (1.92%)	157
S.3	10.8	145	165	–	49 (94.2%)	11 (20.4%)	180
S.4	8.3	145	160	220	50 (89.2%)	2 (3.8%)	179
S.5	8.8	145	170	–	41 (95.3%)	7 (17.5%)	142
S.6	7.2	135	135	245	55 (96.4%)	0 (0%)	190
S.7	7.3	180	–	230	17 (36.1%)	1 (2.56%)	144
S.10	5.9	115	150	265	9 (16.6%)	0 (0%)	179
S.11	8.6	160	160	–	52 (98.1%)	4 (7.2%)	182
S.12	6.6	165	175	250	29 (54.7%)	0 (0%)	168
X	**7.8**	**146**	**158**	**236**	**35.8 (70.1%)**	**2.6 (5.3%)**	**171**

For an explanation of the columns see Table 1. For responses to the obstacle we distinguish between ones in the direction of motion and ones in the appropriate direction for avoiding the obstacle. On average, participants hit less than 1% of the obstacles and missed about 3% of the targets when neither moved. Participants hit the obstacle on less that 2% of the trials when the target jumped, and missed about 8% of the targets when the obstacles jumped the sagittal velocity was averaged across trials (and then subjects) for each condition for every 5 ms from the moment of the change. Again, we estimated when the first response occurred by comparing the sagittal velocity traces across conditions. Since there were two static conditions in this experiment, one for each initial position of the obstacle, it was not possible to directly compare the velocity traces obtained from trials in which either the target or the obstacle jumped (as in the first experiment). To make the two relevant comparisons for individual subjects, we first subtracted the median value of the corresponding static condition from the value obtained when either the target or the obstacle jumped (for every 5 ms of the velocity trace). Then, as in the first experiment, we calculated one-tailed *t* tests, independently for each point in time, to determine the latency of the response. For the response to the obstacle, two independent sets of one-tailed *t* tests were conducted: one to evaluate responses in the direction of (apparent) motion and the other to do so for responses in the correct direction for avoiding the obstacle.

Results

The central part of Fig. 3 shows the average velocity in the sagittal direction for each of the conditions. Like in Fig. 2, static trials are shown in green, trials in which the target jumped are shown in blue, and trials in which the obstacle jumped are shown in red. Because we used two different initial positions of the obstacle in this experiment, the figure shows two kinds of static trials: represented by the dotted and continuous green lines. For the target jumps and obstacle jumps conditions, continuous and dotted lines each represent displacements in the same direction.

Again we first estimated the time needed to respond to the manipulations by visually judging where the lines of the different conditions separate. The velocity profiles for the trials in which either the target or the obstacle jumped were compared to the corresponding static trials (those which started with the target and obstacle at the same position). This comparison confirmed that it takes subjects slightly shorter to react to the target changing position (blue arrows in Fig. 3) than to react to the obstacle changing position (red arrows). Most importantly, we found that the initial response to the obstacle was in the wrong direction! The hand initially moved in the same direction as the obstacle. The incorrect response in the direction of obstacle motion was later followed by a response in the opposite direction, appropriate for the new obstacle position.

The bottom part of Fig. 3 shows the total number of subjects for whom the hand's velocity was significantly different from unperturbed movements at each point in time. The blue line is for trials in which the target jumped. The light and dark red lines are for responses in the direction of motion and opposite the direction of motion of the obstacle, respectively. Table 2 gives the latencies of the responses to the target, and of both kind of responses to the obstacle displacement, for each of the subjects. The moment at which subjects start to reliably respond to the target jump is more variable in this experiment, probably because the initial conditions were different from those of the previous experiment, and because of having to consider the velocity traces on trials in which neither the target nor the obstacle jumped in the analysis.

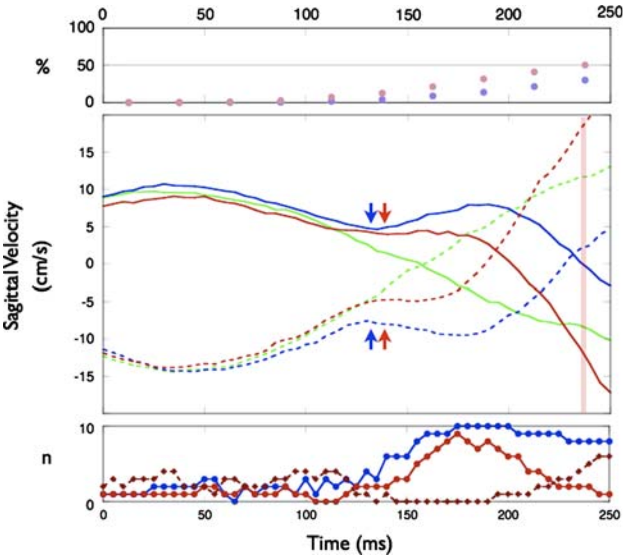

Fig. 3 Results of experiment 2. Time is measured from the moment at which the target or obstacle could jump to a new position. *Green* no jump. In this case there were two kinds of static trials because there were two different initial positions of the obstacle. *Blue* target jumps. *Red* obstacle jumps. *Continuous* and *dotted lines* represent the two directions of the displacements. *Central panel* average signed velocity of the hand in the direction orthogonal to the main direction of motion. *Arrows* indicate our visual estimate of the latency of the response. *Bottom panel* number of subjects for whom the hand's velocity was significantly different for the two directions of the displacement (see main text for more details). For the obstacle, both responses in the direction of motion (*light red*) and those in the appropriate direction for avoiding the obstacle (*dark red*) are shown. *Top panel* percentage of trials in which the hand has reached the obstacle or target. The moment at which the hand had done so on 50% of the trials is also indicated by the *thick vertical lines* in the *central panel*

Our first significant response occurred 105 ms after the displacement of the target. Most subjects responded between 135 and 160 ms after the target jump (on average about 145 ms). For the obstacle we found that the first significant responses occurred 130 ms after it jumped and they were in the direction of motion (light red), with the slowest responses in this direction after 180 ms (on average, the latency of this response was about 160 ms). The second response (dark red) was opposite the direction of motion and was adequate for the obstacle displacement. Such responses started to reach significance about 50 ms later than the initial responses, which is about 200 ms after the change for the first subjects who showed an effect and even later (up to 265 ms) for the rest of them (on average about 235 ms).

Subjects moved more slowly in this experiment than in the first one. This can be seen in Table 2, and in the upper panel of Fig.3 that shows the percentage of trials in which the hand had reached the positions of the obstacle (light red) and the target (light blue) at each moment in time. At the time at which the hand had reached the obstacle position on 50% of the trials (thick vertical line across the central panel of the figure) the responses to the obstacle motion (those in the same direction of the displacement) had already been replaced by an adequate response to the new obstacle location (in the opposite direction than the displacement). Nevertheless, subjects' responses were not effective in avoiding the obstacle when its position changed: on average the obstacle was hit on 70% of the trials in which it jumped, while subjects only missed 5% of the targets that jumped. Note that if subjects had not responded to the jumps at all, they would have hit fewer obstacles as well as targets (50% of each). The fact that they did quickly respond to changes in obstacle position, even though doing so was ineffective, suggests that they either cannot help doing so, or else that they took the instruction to avoid the obstacle seriously despite finding themselves unable to fulfill this part of the task. In fact, the incorrect response to the obstacle jump sometimes made subjects miss the target: they missed the target on 8% of the trials in which the obstacle changed position. As in the first experiment, there were big differences in performance between subjects (see Table 2). It is clear that the faster subjects almost always hit the obstacle when it moved and regularly missed the target.

Discussion

The second experiment was designed to clarify whether the results of our first experiment resulted from a true response to the requirements imposed by the obstacles after the jump, or could be explained as an automatic response to the retinal motion signal. To distinguish between the two possibilities we made sure that the appropriate correction of the movement was in the opposite direction than the obstacle's displacement.

It is immediately evident from our results that the first response to the displacement of the obstacle was in the same direction as the displacement itself. It is therefore more appropriate to consider it to be a response to the motion signal, than to consider it to be a true adjustment to the new requirements. On average subjects' responses to the retinal motion signal took about 160 ms. Interestingly, we also found a second response, which only occurred about 235 ms after the manipulation, but was in the correct direction for avoiding the obstacle. This response can probably be seen as a true adjustment to the new constraints, although we cannot be completely sure that it is not just a response to the incorrect adjustment in the direction of motion. Taken together, we think that these results show that a change in obstacle position can quickly influence our actions, but that such a fast response does not consider the constraints imposed by the new position of the obstacle. Instead it is a simple reaction to the motion itself. If this interpretation is correct, we predict that subjects will be unable to respond quickly to a new obstacle position if there is no clear direction of obstacle motion.

Experiment 3

In order to confirm our interpretation that fast responses to obstacle jumps are driven by perceived motion we decided to test the above-mentioned prediction. By doing so we may also obtain a better estimate of the latency of responses that do consider the new constraints imposed by the displaced obstacle. In our final experiment two obstacles were presented (as in the first experiment), but this time the separation between the obstacles was initially much wider. On some trials the two obstacles changed their positions in opposite directions, reducing the size of the opening to that of the first experiment. They moved by slightly different amounts, so that the final positions were identical to those in the first experiment (after the obstacles' positions had changed; see lower panel in Fig. 1). In this way the apparent motion of the two obstacles was in opposite directions, so direction of motion did not specify the direction of the required response (i.e. the position of the opening). Note that on trials in which the obstacles moved, the final constraints in this experiment are identical to those in the first experiment.

If our hypothesis is correct that unspecific motion is the information source underlying fast adjustments to the movement of the obstacles in the previous experiments, subjects should not respond quickly to the change in this experiment. This should allow us to isolate a later response in the adequate direction, if what we saw in the second experiment was a true response to the obstacle and not a response to first having moved in the wrong direction, and will therefore enable us to determine its latency (in Fig. 3, and also in our analysis of the different responses to the obstacle displacement presented in Table 2, the onset of the second response is masked by the consequences of the initial incorrect response).

Methods

Participants

The three authors and seven of our colleagues, six of whom had participated in either one or both previous experiments, took part in this experiment (6 males and 4 females; ages ranging from 24 to 48). Except for one subject all reported to be right-handed. The left-handed subject performed the task moving from left to right, as in the first experiment.

Procedure

The task and experimental procedures were similar to those used in the previous experiments, with the following exceptions. Two obstacles were presented which initially left an opening of 18 cm between them (see lower panel in Fig. 1). When the obstacles jumped, one moved 5 cm and the other moved 9 cm, in opposite directions, so that the size and possible positions of the opening after the change were identical to those of the first experiment. Thus both directions of motion (upward and downward) were presented each time the obstacles jumped. To avoid the obstacles, subjects had to correctly determine the position of the opening after the manipulation. As in the previous experiments the target and obstacles were *static* on 40% of the trials. In the remaining trials either the *target jumped* 2 cm or both *obstacles jumped* (each on 30% of the trials). Trials of the different conditions were presented in random order. Each subject performed a total of 400 trials distributed across two sessions of 200 trials each. Sessions lasted about 45 min.

Data analysis

The data were analyzed in the same way as in the previous experiments. In this case 12% of the trials were discarded for technical reasons or because the manipulation occurred before the hand started to move. In short, movement trajectories and velocities were calculated from the x–y positions that were recorded with the tablet. For each condition, the sagittal velocity was averaged across trials and subjects for every 5 ms from the moment of the change. We estimated when the first response occurred by comparing the sagittal velocity traces across conditions. The two relevant comparisons between the velocity traces of the two conditions with a target displacement and the two with obstacle displacements were evaluated with one-tailed t tests, independently for each point in time and for each subject.

Results

The average sagittal velocity in each of the conditions is shown in the central part of Fig. 4. As in the previous figures, static trials are shown in green, trials in which the target jumps are shown in blue, and trials in which the obstacles jump are shown in red. Continuous and dotted lines represent the two directions in which the target or the opening between the obstacles could be displaced.

As in the previous experiments, visual inspection of the figure (determining the point at which the lines of the different conditions separate) suggests that it took subjects about 120 ms to react to a change in the position of the target (blue arrow), and just under 200 ms to respond when the obstacles moved (red arrow). We also evaluated the differences between the velocity traces using one-tailed t tests (independently for each subject and each point in time). The response times obtained with this method are presented in Table 3. The bottom part of Fig. 4 shows the total number of subjects for whom the hand's velocity was significantly different at that point in time. The fastest significant response to the target jump occurred after

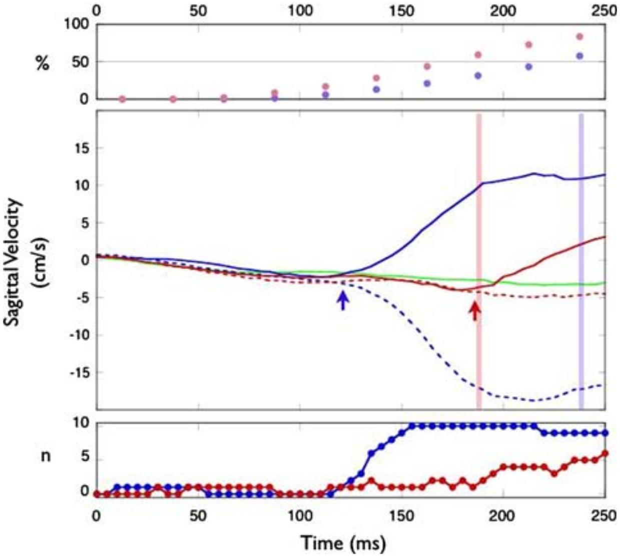

Fig. 4 Results of experiment 3 . Time is measured from the moment at which the target or obstacles could jump to a new position. *Green* no jump. *Blue* target jumps. *Red* obstacles jump. *Continuous lines* and *dotted lines* represent the two kinds of displacements. *Central panel* average signed velocity of the hand in the direction orthogonal to the main direction of motion. *Arrows* indicate our visual estimate of the latency of the response. *Bottom panel* number of subjects for whom the hand's velocity was significantly different for the two kinds of jump. *Top panel* percentage of trials in which the hand has reached the obstacle or target. The moment at which the hand had done so on 50% of the trials is also indicated by the *thick vertical lines* in the *central panel*

Table 3 Individual results in experiment 3

	Leftward velocity	Response to target (ms)	Response to obstacle (ms)	Obstacle hits	Target missed	Valid trials
S.1	7.9	140	200	54 (47.3%)	3 (2.5%)	385
S.2	9.4	160	240	51 (45.9%)	11 (10%)	357
S.3	11.4	135	–	51 (47.6%)	25 (23.5%)	360
S.4	11.1	130	–	53 (50%)	19 (19.3%)	338
S.5	9.4	125	235	43 (45.2%)	5 (5%)	322
S.8	9.7	140	170	52 (48.5%)	12 (11%)	358
S.9	7.9	145	255	46 (48.4%)	9 (9%)	326
S.10	6.6	155	195	28 (26.4%)	1 (1%)	348
S.11	7.4	150	225	45 (39.1%)	5 (4.3%)	379
S.13	7.1	140	–	49 (43.3%)	4 (3%)	362
X	**8.8**	**142**	**217**	**47.2 (44.1%)**	**9.4 (8.8%)**	**354**

For an explanation of the columns see Table 1. In this case the maximum possible number of valid trials was 400. Participants never hit the obstacles and missed less than 0.5% of the targets when neither moved. Participants also never hit an obstacle when the target jumped, and they missed less than 0.1% of the targets when the obstacles jumped

125 ms. As can be seen in the table and the figure, most subjects show a significant response to the target jump by 150 ms after the change (blue symbols and line), with an average latency of 142 ms. For the obstacle (red symbols and line) the number of subjects with a significant response started to increase much later (170 ms for the fastest response; on average about 220 ms) and the increase itself was much more gradual.

These results support our interpretation that the fast responses to the changes in obstacle position in the other two experiments were reactions to the perceived motion rather than specific responses to the new positions of the obstacles. In this last experiment we found that responses that considered the constraints imposed by the new obstacle positions took much longer. On average they took about 220 ms, which is close to the time needed to initiate a new action. This long latency of the adjustment of the hand's path meant that the response to the changed positions of the obstacles often occurred too late. As in the previous experiments, by the time that the first response to the obstacle jump occurred, the hand had already reached the obstacle in about 50% of the trials (thick vertical light red line across the central panel of the figure). Consequently, on average subjects hit an obstacle on 44% of the trials in which the obstacles jumped, while they only missed the target on 9% of trials in which it jumped (without any correction, for approximately straight movements, both values would be 50%). As in the previous experiments, there were big differences between subjects in the frequency of obstacle hits and target misses (see Table 3), and again we can see that the faster subjects hit the obstacles and miss the target more often than the slower subjects.

Discussion

The third experiment was designed to verify that the fast responses to displacements of the obstacles in the previous experiments were due to the motion signal associated with the displacement, and to determine the latency with which people can respond to the new constraints imposed by an obstacle after it jumped. By displacing both obstacles simultaneously in opposite directions we made sure that the direction of retinal motion was not informative about the final position of the opening. Our results showed that subjects needed much longer to respond to the obstacle in this case (on average about 220 ms), which supports our interpretation that the fast responses to the obstacles jumping in experiments 1 and 2 were a direct reaction to the motion in the surrounding. Note that in this experiment the responses that we did find must be true responses to the new constraints imposed by the changed obstacle positions, rather than corrections to initial erroneous responses, because there were no such initial fast responses. The responses to the obstacle position in this experiment had slightly shorter latencies than those in the second experiment 2, but that is probably just due to the fact that the hand was already moving in the wrong direction when it started to respond adequately in the previous experiment. Thus the latency values in Table 3 probably give a better estimate of the true latency for responding to new constraints on the movement than do the corresponding values in Table 2.

Subject's responses to the target jump were quite consistent across the three experiments: the fastest responses that we found always took about 120 ms. Considering that both the target and the obstacles could jump, and therefore produce a motion signal, the systematic differences that we have found between the latencies of responses to motion of targets and obstacles suggests that targets and obstacles are not treated in the same way when controlling hand movements.

General discussion

In a series of three experiments we analyzed the timing of hand responses to a change in the position of either the target of the movement or obstacles in the environment. In the first experiment we found that the responses to the change in the position of the obstacles took only slightly longer than the responses to the target jump (on average 180 ms instead of the 150 ms needed to respond to the target). The results of the second experiment showed that these fast responses to the displacement of the obstacle could just be a reaction to the motion signal produced by the change in the position of the obstacle. The results of the third experiment showed that adjustments that consider the constraints imposed by the changed obstacle position take considerably longer (on average about 220 ms).

Taken together, the present results suggest that targets and obstacles are treated differently when controlling hand movements. It has been shown that specialized pathways through the parietal cortex continuously monitor target position so that the hand's trajectory can rapidly be adjusted during its movement (Desmurget et al. 1999; Gréa et al. 2002; Pisella et al. 2000). Our results suggest that obstacles might not have access to such dedicated pathways. It is unlikely that having two goals (i.e. reaching the target and avoiding the obstacle) in itself is problematic, because it is possible to make simultaneous independent on-line adjustments when reaching for two separate targets bimanually (Diedrichsen et al. 2004). It is also unlikely that determining on-line what kind of adjustment is needed after the obstacle changes position is simply too complicated, because in our second experiment the obstacle could only jump to a single other position, so a single alternative strategy could have been set into action as soon as the obstacle was seen to move. So why did responses to the obstacles' displacement take longer than those to the target's displacement?

One possibility is that the subjects' attention was directed towards the target because they considered it to be more important to hit the target than to avoid the obstacles (Castiello 1996). In our experiments there was no real reason to attend to the target more than to the obstacles, because they jumped equally often and subjects received more or less the same "punishment" for missing the target as for hitting the obstacle (having to look at a message on the screen for several seconds). However, it is possible that some subjects did that. In Table 2, for example, there are a few cases of participants who reached the target on all trials in which it moved, but almost always hit the obstacle when it was displaced. This could result from the target being considered more important than the obstacle. Perhaps they failed to consider the virtual obstacles as real obstacles. Other participants, on the other hand, did manage to avoid the obstacles (for which they varied their movement speed across the experiments) and they too show a difference in timing between their responses to the target and the obstacle. Therefore, we do not think that our results can simply be explained by assuming that the obstacles were considered less important than the target.

The fast responses that we found even when such responses were counterproductive are consistent with previous results which show that even irrelevant *obstacles* or *distracters* influence hand movements (Gangitano et al. 1998; Howard and Tipper 1997; Jackson et al. 1995; Kritikos et al. 2000; Meegan and Tipper 1998; Mon-Williams et al. 2001; Pratt and Abrams 1994; Saling et al. 1998; Tipper et al. 1997). One way to judge whether subjects paid more attention to the target than the obstacles would be to measure eye movements during the execution of the task, but we did not do so. However, other studies have shown that subjects tend to fixate a point between the target and other objects when they are in close proximity to each other (Findlay 1982; Sailer et al. 2002a; Sailer et al. 2002b). It is possible that our subjects did that, as a way to optimize their chances of responding to both the target and the obstacles' displacement, but from the results of the present study we cannot know whether this was the case. An alternative explanation for longer response times for obstacle displacements is that responses to obstacles are specifically "inhibited". Several authors have suggested that other objects than the target activate a motor response that needs to be suppressed (Castiello 1999; Howard and Tipper 1997; Jackson and Husain 1997; Jackson et al. 1995; Kritikos et al. 2000; Meegan and Tipper 1998; Pratt and Abrams 1994; Tipper et al. 1997; Tipper et al. 1992). Since our obstacles are quite similar to the target and also not "real" (in the sense that they do not physically obstruct the movement), it is possible that both the target and the obstacles activated responses and that those toward the obstacle were suppressed. But we do not think that this was an issue in our experiments. Most participants showed a response to the obstacles' displacement (see Tables 1, 2, 3), independently of whether it really helped to avoid the obstacle or not. This suggests that although our obstacles were mere projections without physical entity, participants did consider them as a constraint for the movement, rather than just as distracters (Tresilian 1998, 1999), and therefore tried to avoid them rather than just ignoring them once the movement had started. Moreover, we also found fast responses to the displacement of the obstacles in the first two experiments, which should not have occurred if responses to the obstacles were simply suppressed.

One of the reviewers suggested that subjects may have learnt to respond to any movement in the display as a way to respond quickly to the displacements in our experiments. This explanation is consistent with our proposal that the fast responses to the displacement of the obstacles in the first two experiments were a direct reaction to retinal motion. However, learning to respond in this manner would not explain why responses to displacements of the obstacles took longer than responses to displacements of the target in the first two experiments. Moreover, it is not clear why responding in such a manner would be learnt in our second experiment, where it was only a suitable response on half of the trials in which there was a displacement, but would not be considered in daily life where it is probably often the appropriate response.

The most likely reason for the different response times for target and obstacles is that the hand passes the obstacle first. It is unlikely that the posture at the moment that the subject responds, or the muscles that must be activated to obtain the response, are responsible for the differences, because the target and obstacle are quite close to each other (see Fig. 1), whereas the hand was at very different positions on different trials and for different subjects (see very shallow slopes in top panels of Figs. 2, 3, 4). The fact that the hand passes the obstacle first introduces different constraints for the two kinds of perturbations because participants have to hit the target after passing the obstacle, whereas they have no further constraints after hitting the target. Changing the path towards a given target position is presumably more difficult than changing the target position alone. Re-calculating the hand's trajectory, taking into account the new position of the obstacle while still getting to the target, presumably requires more time than simply adjusting the movement to where the target is now. It could then be expected that the fastest subjects would have the most problems to respond to an obstacle jump, since they have least time available for corrections, which is what we found. In support of this distinction it should also be noted that people can respond quickly to obstacles when doing so does not interfere with other goals (as when avoiding stepping on obstacles during walking; Weerdesteyn et al. 2004), whereas we here show that they cannot do so when avoiding the obstacle is secondary to reaching a target.

So how do we cope with moving obstacles in daily life? Perhaps we can normally tolerate the slightly longer latency when dealing with obstacles by making sure to keep a safe distance from obstacles, so that the hand is unlikely to collide with the obstacles anyway (Dean and Brüwer 1994; Tresilian 1998). Quickly responding to motion near the path may usually also help deal with unexpected movements of obstacles, like it did in our first experiment. However, in daily life obstacles seldom suddenly appear (as in the third experiment) and the appropriate response is seldom in the opposite direction than the motion (as in the second experiment), so we can trust that initially moving in the same direction as a moving obstacle, and then refining the adjustment if necessary and if there is enough time, will be adequate for avoiding collisions in the majority of cases.

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