



Hitting a target is fundamentally different from avoiding obstacles



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ABSTRACT

To successfully move our hand to a target, it is important not only to consider the target of our movements but also to consider other objects in the environment that may act as obstacles. We previously found that the time needed to respond to a change in position was considerably longer for a displacement of an obstacle than for a displacement of the target (Aivar, Brenner, & Smeets, 2008, *Experimental Brain Research* 190, 251–264). In that study, the movement constraints imposed by the obstacles differed from those imposed by the target. To examine whether the latency is really different for targets and obstacles, irrespective of any constraints they impose, we modified the design of the previous experiment to make sure that the constraints were matched. In each trial, two aligned ‘objects’ of the same size were presented at different distances to the left of the initial position of the hand. Each of these objects could either be a *target* or a *gap* (opening between two obstacles). Participants were instructed to pass through both objects. All possible combinations of these two objects were tested: gap–target, target–gap, gap–gap, target–target. On some trials one of the objects changed position after movement onset. Participants systematically responded faster to the displacement of a target than to the displacement of a gap at the same location. We conclude that targets are prioritized over obstacles in movement control.

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1. Introduction

In daily life our movements are not only determined by the objects that we are interested in, but also by the many surrounding objects that can be considered as obstacles for reaching the object of interest. Many studies have shown that obstacles close to the path to a target have an effect on the movement trajectory (Chapman & Goodale, 2008, 2010b; Mon-Williams et al., 2001; Sabes & Jordan, 1997; Saling et al., 1998; Tipper, Howard, & Jackson, 1997; Tipper, Lortie, & Baylis, 1992; Tresilian, 1998; Verheij, Brenner, & Smeets, 2014). In our dynamic environment, in which there are other actors besides ourselves simultaneously trying to perform different goal-directed actions, objects can change position and suddenly appear in the path to our goal. Many studies have shown that people can respond very quickly (in about 120 ms) when the position of the target of the movement changes unexpectedly (Brenner & Smeets, 1997, 2003, 2004; Day & Lyon, 2000; Oostwoud Wijdenes, Brenner, & Smeets, 2011; Prablanc & Martin, 1992; Soechting & Lacquaniti, 1983; Veerman, Brenner, & Smeets, 2008). It has also been shown that we take obstacles into

account when responding to changes in target position during the movement (Chapman & Goodale, 2010), and when responding to mechanical perturbations of the arm (Nashed, Crevecoeur, & Scott, 2012). However it is still not clear how quickly hand movements can be adjusted in response to a change in the position of other objects than the target, such as obstacles.

In a previous study, we examined how obstacles and targets are dealt with in dynamic environments by analyzing hand movement corrections in two kinds of trials: trials in which the target was displaced and trials in which one or more obstacles were displaced (Aivar, Brenner, & Smeets, 2008). In one case (Experiment 1), participants had to reach the target through a gap between the obstacles *before* reaching the target. We interpreted these results as suggesting that obstacles are processed with longer latencies than targets. The latency differences could be the result of differences between the time it takes to process visual information about targets and obstacles. Alternatively, the latency differences could

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have to do with the different constraints that the targets and obstacles imposed on the hand's trajectory. Targets and obstacles differed in several respects in our previous study. Targets were always white, 4 cm long rectangles, while obstacles had different sizes and moved differently in each of the reported experiments (see Fig. 1 of Aivar, Brenner, & Smeets, 2008).

The main purpose of the present study was to examine whether the latency is different for targets and obstacles, irrespective of any kinematic constraints. In each trial, the task was to move through two equally sized ranges of positions (which we refer to as 'objects'), which could each either be a *target* or a *gap*. *Targets* were rectangles whereas *gaps* were rectangular spaces between obstacles. Participants were instructed to hit the targets and pass through the gaps. In separate experiments we tested different combinations of objects (targets and gaps).

2. General methods

The two main experiments and a third, control experiment, were all performed with the same procedure and equipment, and the data was analyzed in the same way. We will therefore present the general methods in this section and specify the few things that differed between experiments later on.

2.1. Participants

All participants reported having normal or corrected to normal vision, to be right-handed, and to have no known neuromuscular deficits. All participants gave their informed consent to participate in the experiment, which is part of an ongoing research project that has been approved by the ethics committee of the Faculty of Human Movement Sciences of VU University in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki) for experiments involving humans.

2.2. Set-up

We used a graphic tablet (Wacom A2) to record the two-dimensional position of a hand-held stylus at a frequency of 200 Hz throughout the experiments. The graphic tablet was placed horizontally on a standard table. Participants sat comfortably in a chair in front of the graphic tablet and held the stylus in their right hand. Stimuli were projected onto a surface above the tablet that was visible through a semi-transparent mirror so that the image appeared to be on the tablet. Lamps illuminating the space between the mirror and the tablet allowed participants to also see their hand during the experiments. The resolution of the display was 1024×768 pixels, with each pixel corresponding to approximately 0.5 mm on the surface of the tablet.

2.3. Task

The task was to slide a stylus from right to left across the graphic tablet while moving through two objects. At the beginning of each trial a red circle (1 cm diameter), indicating the *starting position*, was presented on the right side of the tablet. The rest of the tablet was empty. Soon after the stylus was placed at the starting position, the two objects that one was to move through were presented simultaneously on the tablet. This was the signal to begin the movement through *both* objects. The combinations of targets and gaps that could serve as pairs of objects varied between experiments. The first object was always 25 cm to the left of the starting position, while the second was always 5 cm further to the left, so the hand mainly had to move laterally. A target was a 4×1 cm rectangle that was oriented so that the long side was

orthogonal to the movement direction (represented in blue in Fig. 1). A gap consisted of two aligned large rectangles (19×1 cm) with a 4 cm gap between them (represented in red in Fig. 1).

At the beginning of each trial, both objects were aligned with the starting position. In 20% of the trials neither object moved. In the remaining trials (perturbation trials) either the first object or the second object jumped to a new position. This jump occurred 350 ms after the stimuli were presented. Its amplitude was always 2 cm in a sagittal direction, perpendicular to the main direction of movement. Half the jumps were away from the participant and the other half were towards the participant. We expect responses to such jumps in the sagittal direction. On most trials the hand was already moving when the jump occurred (if not, the trial was not analyzed; see below). On average the hand position at the time of the jump was less than 4 cm from the starting position. Trials were considered to have ended once the stylus moved further than 30 cm to the left of the starting position (i.e. once it passed the second object).

Participants were instructed to perform fast movements but also to always avoid the obstacle(s) (i.e. to pass through the gap) and hit the target(s). It was emphasized that it was as important to hit targets as to avoid obstacles. The hand, targets and obstacles were continuously visible during the movement. After each trial, feedback was presented in the form of a message on the screen informing participants about their performance. This feedback was positive if all targets were hit and obstacles avoided, and the movement was completed within 800 ms. Otherwise, negative feedback specified whether the movement took longer than 800 ms, an obstacle was hit, or a target was missed.

Participants performed 4 blocks of 50 trials each in a single continuous session. The configuration remained the same for all trials within a block. In each block the five different perturbations (static plus four different jumps) were each presented 10 times in random order. Each of the two configurations that were used in an experiment was presented in two of the four blocks. Block order was counterbalanced across participants. Thus, each participant performed a total of 200 trials (two blocks of 50 trials per configuration) in a single session that lasted about 20 min. Of the 100 trials that were recorded for each of the two configurations within a session, 20 trials were static and 80 were perturbed (each combination of 2 objects that could jump and 2 possible directions of the jumps occurred 10 times in each of the 2 blocks).

2.4. Data analysis: movement kinematics

We only considered trials in which the hand started to move before the jump occurred and moved 30 cm to the left (ending the trial) within 800 ms. All trials that met these conditions were included in the analysis, regardless of other aspects of performance. We evaluated the overall performance by calculating the percentage of obstacle hits and target misses for each kind of perturbation. We did so for each of the configurations that were presented.

The measured tablet positions were used to obtain movement paths and velocity profiles. We calculated velocities by dividing the distance between consecutive samples by the sampling interval (5 ms). Occasional missing data points were estimated by linear interpolation. No other smoothing algorithms were used, so the original temporal resolution of the measurement was not compromised. To determine the start of the movement for each trial, the peak in the tangential velocity profile was found and then the beginning of the movement was determined by looking backwards in time for the last velocity value that was not 0. As already mentioned, the end of the movement was when the stylus passed the

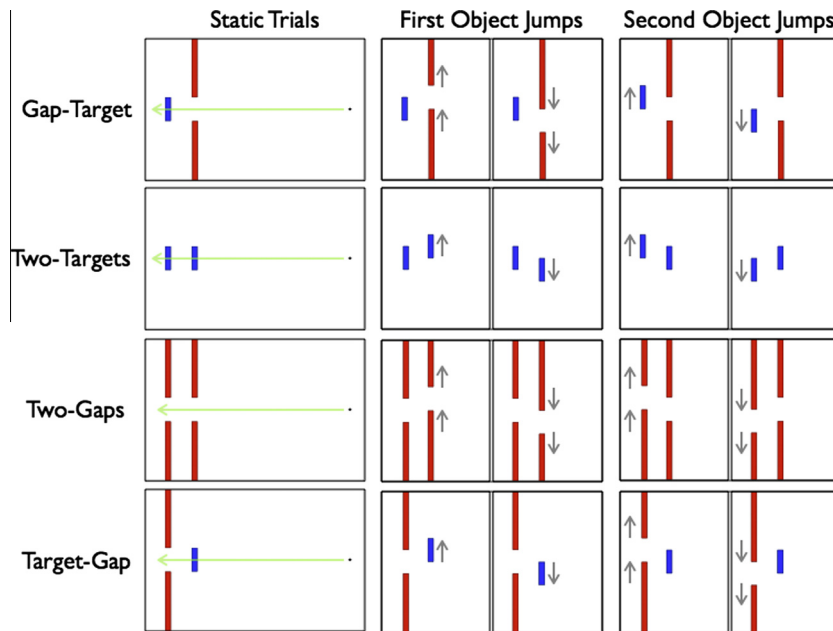


Fig. 1. Schematic representation of the objects and positions used in the three experiments (top view, not to scale). The colors (blue target, red obstacles, black starting position) are chosen for consistency with the following figures, and do not always correspond to the colors used in the experiments. The first column (*static trials*) shows the four possible configurations of objects at the start of a trial. The second column (*first object jumps*) shows the configurations after the first object jumped. The third column (*second object jumps*) shows the configurations after the second object jumped. The grey arrows indicate the direction of the jump; the green arrows indicate possible movement vectors in static trials. In each experiment only two of the four possible configurations were presented: the upper two rows in experiment 1, the lower two rows in experiment 2, and the middle two rows in experiment 3 (control).

second position. Note that the stylus was still moving fast at that moment.

The total duration of the movement, the peak velocity and the proportion of time before peak velocity were determined for each trial, and then averaged across replications for each participant. For each experiment, differences in movement kinematics between the conditions were evaluated by subjecting these averaged measures to repeated measures ANOVAs. Two factors were considered in the analysis: *configuration* (2 levels, as only two of the four possible combinations of targets and gaps were presented in each experiment) and *perturbation* (5 levels: static, first object jumps up, first object jumps down, second object jumps up and second object jumps down). The Greenhouse–Geisser correction was used when the sphericity requirement was not met. Significant effects of perturbation were followed by a paired comparison between the static and the other perturbations. A probability value below 0.05 was taken as statistically significant in all analyses. To compare movement paths across conditions, each movement trajectory was divided into 99 segments of equal length, so that the path was represented by 100 equidistant data points, and these points were averaged across replications and participants. To compare patterns of movement speed across conditions, lateral velocity profiles were calculated for each trial, and then synchronized on movement onset and averaged across replications and participants.

Errors were determined from the (linearly interpolated) paths of the stylus with respect to the different objects. If the stylus' path at the object's lateral position was inside one of the obstacles (i.e. outside the gap) we considered the obstacle to have been hit. If the stylus' path at the object's lateral position was outside the target we considered the target to have been missed. Error rates were defined as the total percentage of trials in which a target was missed or an obstacle was hit. Individual error rates were determined as a general measure of participants' performance. To determine how the differences between the configurations influence performance, average error rates were also estimated separately for each participant and experimental condition, and error rates

for equivalent object jumps in the two configuration were compared with paired *t*-tests.

2.5. Data analysis: response to displacement

As discussed above, the main purpose of this experiment was to compare participants' responses to target displacements with their responses to displacements of gaps. The displacements were always perpendicular to the direction of movement, so we examined corrections in the sagittal direction. We estimated the latencies of responses to the different perturbations by comparing the sagittal velocity traces for opposite directions of the jump. For each participant, we used one-tailed *t* tests to compare the sagittal velocities of trials that only differed in the direction of the jump (jumping closer to the body or away from the body). For every 5 ms from 50 ms after the jump, we determined whether the comparison between the traces changed from not being significant to being significant and then remained significant for at least four additional data points (25 ms). The time of the first of these significant data points was considered to be the latency. Mean response latencies to the different object jumps in each experiment were compared with paired-samples *t*-tests.

To help relate the time at which responses to the jumps occurred to the hand's position on its trajectory, we calculated the percentage of trials in which the stylus had passed the center of each of the objects for each moment in time (every 5 ms; considering all participants). The time at which the hand had passed each of the objects in half the trials is indicated in the sagittal velocity profiles.

3. Experiment 1

In Experiment 1 we presented two different configurations of objects. In *Gap-Target* we presented a gap and a target and asked participants to reach the target by passing through the gap between the obstacles (this condition is similar to the obstacles

condition used in Experiment 1 in Aivar, Brenner, & Smeets, 2008). In *Two-Targets* we replaced the gap by another target and asked participants to hit both targets in sequence (see first and second row in Fig. 1). Although both configurations were different in instructions and visual appearance, the kinematic requirements were identical because the same spatial constraints applied to the hand's trajectory.

3.1. Methods

3.1.1. Participants

Two of the authors and eight colleagues voluntarily took part in Experiment 1 (2 males and 8 females, ages ranging from 22 to 52). Except for the authors, participants were unaware of the purpose of the study, although most of them had previous experience with similar tasks and were familiar with the experimental setting.

3.1.2. Stimuli

In the *Gap-Target configuration* (upper row of Fig. 1) we presented a gap between a pair of large red rectangles as the first object and a white target as the second object (represented in blue in Fig. 1). In the *Two-Targets configuration* (second row of Fig. 1) both objects consisted of a white rectangle.

3.2. Results

A total of 314 trials (15%) were eliminated either because the jump occurred before the movement started or because participants took more than 800 ms to complete the trial. Table 1 (upper part) shows the total number of trials considered in the analysis for each of the participants in this experiment.

3.2.1. Movement characteristics

Table 2 (upper part) summarizes the kinematics in this experiment. The statistical analysis showed no significant effects of configuration (two levels: *Gap-Target* versus *Two-Targets*) for any dependent variable (total duration of movement: $F_{(1,9)} = 0.092$, $p = 0.768$; peak velocity: $F_{(1,9)} = 0.274$, $p = 0.614$; proportion of time to peak velocity: $F_{(1,9)} = 0.458$, $p = 0.515$). For perturbation (five levels: static and four kinds of jumps) we did find a significant effect for total duration of movement ($F_{(4,36)} = 4.568$, $p = 0.004$), but not for peak velocity ($F_{(4,36)} = 1.538$, $p = 0.212$) or proportion of time to peak velocity ($F_{(1,313,11,819)} = 2.792$, $p = 0.115$). Pre-planned contrasts showed that the differences between static trials and trials with jumps were significant: the static trials were faster. None of the interactions reached significance for any of the kinematic variables considered.

A difference between static trials and trials with jumps was also obvious in performance (see upper part of Table 3). Errors appeared in less than 1% of the static trials. The percentage of errors in trials with jumps was much higher, as can be seen in Fig. 2. The highest error rates occurred in trials in which a gap jumped. Paired samples *t*-test showed a significant difference between average error rates when the first object jumped (gap versus target: $t_{(9)} = 3.696$, $p = 0.005$), but not when the second object jumped (target versus target: $t_{(9)} = 0.208$, $p = 0.84$). It is interesting to mention that correcting the movement to adapt to one of the displacements sometimes came at the price of making an error when dealing with the other object: participants often missed the second object in trials in which the first object jumped (Table 3). Individual differences in the global error rate can be seen in Table 1. In summary, going through a gap that jumped while moving towards a target gave rise to more errors than did passing through a target that jumped while moving to a second target.

3.2.2. Differences between conditions

Fig. 3 presents the main results of Experiment 1. The response to a jump of the first object on the hand's path was faster when the first object was a target (Fig. 3F, continuous blue curve and thick blue arrow) than when it was a gap (Fig. 3C, red curve and arrow). On average the response started 113 ms (SEM = 4.6) after a target jump, and 153.5 ms (SEM = 6.7) after a gap jump at the same location (Table 1). For the target, the response in the direction of the jump was completed by the time the hand had passed the target in 50% of the trials (vertical continuous blue line). For the gap, the peak response occurred just before the hand had passed the gap in 50% of the trials (vertical red line). The main response to a jump of the second object (always a target) occurred later than the response to a jump of the first object, although there was also an early response that approximately coincided in time with the response to the first object's jump. The peak response was just after the hand had passed the second target in 50% of the trials (vertical dashed lines) and was larger than the response to the first object jumping, probably because there was no need to limit the extent of the adjustment because the trajectory after passing the second object is irrelevant (see average traces, Fig. 3A and D). The average latencies of the responses were significantly different when the first object jumped (gap versus target: $t_{(9)} = 7.650$, $p < 0.001$), but not when the second object jumped (target versus target: $t_{(9)} = 1.970$, $p = 0.080$). Response onsets in the two configurations varied across participants (see Table 1 and bottom parts of sagittal velocity profiles in Fig. 3C and F), but the differences between both kinds of objects were very systematic: it always took longer to respond when a gap jumped than when a target did so (on average about 40 ms longer). The average lateral velocity traces in Fig. 3B and E show that on average the objects jumped well before peak velocity (grey lines), which means that the initial sagittal responses occurred near the time of maximal lateral velocity. Note that the velocity of the unperturbed movement (green curve) is slightly higher than the other curves during the second half of the movement, but the lateral velocity profiles remained bell shaped when an object jumped. Thus, participants did not decelerate substantially in response to the object jumps.

3.3. Discussion

In Experiment 1 we compared hand movement performance in two configurations: *Gap-Target* and *Two-Targets* (upper part of Fig. 1). We found that participants corrected their hand's trajectories in response to the displacement of either of the objects on their path (Fig. 3A and D). They did so quickly enough to avoid hitting the obstacles or missing the targets in a high proportion of trials (Fig. 2). They would have often hit obstacles and missed targets if they would not have corrected their movements. The kinematics of the movements were influenced slightly by the changes in the objects' positions. Most importantly, we found a statistically significant difference between response times to target jumps and gap jumps. When the first object along the path was a target that jumped, the average response was 40 ms faster than when the first object was a gap of the same size as the target that jumped by the same amount from the same location (Fig. 3C and F). This difference between gaps and targets appeared consistently for all participants (Table 1). Probably as a result of the difference in latency, the proportion of trials with errors (obstacle hits or target misses) was significantly higher for trials in which a gap jumped (Fig. 2).

These results closely replicate our previous findings (Aivar, Brenner, & Smeets, 2008), which suggested that targets and obstacles are treated differently in movement control. They extend those

Table 1

Individual performance in the three experiments (participants S.1 and S.2 are authors).

	Gap-target task				Two-targets task			
	Trials	Error Rate (%)	Response to 1st object (ms)	Response to 2nd object (ms)	Trials	Error Rate (%)	Response to 1st object (ms)	Response to 2nd object (ms)
S.1	100	7	160	135	100	1	100	140
S.2	86	16	180	250	94	12	135	110
S.3	99	14	170	165	100	8	110	125
S.4	92	18	150	190	85	7	105	210
S.5	92	0	165	300	95	1	110	140
S.6	78	1	120	110	77	12	100	130
S.7	62	1	150	120	74	12	105	120
S.8	96	11	115	115	97	12	100	95
S.9	54	5	170	145	81	7	130	145
S.10	58	7	155	330	66	3	135	130
Mean (SEM)	81.7 (5.5)	10.5 (1.7)	153.5 (6.7)	186 (25.3)	86.9 (3.8)	7.5 (1.4)	113 (4.6)	134.5 (9.6)
	Two-gaps task				Target-gap task			
	Trials	Error Rate (%)	Response to 1st object (ms)	Response to 2nd object (ms)	Trials	Error Rate (%)	Response to 1st object (ms)	Response to 2nd object (ms)
S.1	96	3	135	205	100	0	110	220
S.2	94	18	175	230	90	7	120	245
S.3	100	6	145	225	99	12	115	55
S.4	95	13	175	160	97	15	100	70
S.5	95	5	135	330	96	2	105	125
S.6	98	0	150	335	99	6	115	195
S.11	52	11	175	255	58	9	135	215
S.12	93	28	185	195	89	19	110	200
S.13	92	2	155	240	97	0	120	210
S.14	86	10	145	195	87	14	100	170
Mean (SEM)	90.1 (4.3)	9.6 (2.6)	157.5 (5.8)	237 (18)	91.2 (3.9)	8.3 (2)	113 (3.3)	170.5 (20.6)
	Control: Two-gaps task				Control: Two-targets task			
	Trials	Error Rate (%)	Response to 1st object (ms)	Response to 2nd object (ms)	Trials	Error Rate (%)	Response to 1st object (ms)	Response to 2nd object (ms)
S.1	97	5	160	190	98	1	115	135
S.2	91	13	170	240	92	16	135	140
S.3	94	8	150	180	84	2	125	260
S.11	30	10	155	395	55	2	130	165
Mean (SEM)	78 (10.1)	9.1 (1)	158.7 (2.7)	251.2 (31.4)	82.2 (6)	5.3 (2.3)	126.2 (2.7)	175 (18.3)

findings by ensuring that the difference does not originate in differences between the constraints that the target and obstacle impose on the movement. However, the two tasks that we compared also differ in whether both objects are similar or not: in the configuration in which the first object was a target both objects were the same, whereas in the configuration in which the first object was a gap the two objects were different. We therefore decided to also test the other two possible combinations of objects to ensure that the differences that we found are due to the characteristics of the objects in the path, and do not depend on the similarity between the first and second object.

4. Experiment 2

In Experiment 2 we tested the other two possible combinations of targets and gaps. In the *Two-Gaps configuration* we presented two sets of obstacles separated by gaps. Participants had to pass through both gaps in sequence (third row in Fig. 1). In the *Target-Gap configuration* we presented a target at the first location (closer to the starting point) and a gap at the second location, so participants had to hit the target first and then finish the movement by going through the gap (last row in Fig. 1). Again, although both configurations look very different, kinematically they are identical, since the same spatial constraints apply to the hand's trajectory when moving across a target as when passing through a

gap. The experimental procedures and perturbations were identical to those used in Experiment 1, only the set of configurations employed was different.

4.1. Methods

4.1.1. Participants

Six of the participants from Experiment 1 (including the authors) and four new participants voluntarily took part in this experiment (4 males and 6 females, ages ranging from 23 to 53).

4.1.2. Stimuli

In the *Two-Gaps configuration* both objects consisted of a gap between a pair of large red rectangles (third row of Fig. 1). In the *Target-Gap configuration* we presented a white target as the first object (represented in blue in Fig. 1) and a gap between a pair of large red rectangles as the second object.

4.2. Results

The data were analyzed in the same way as in Experiment 1. A total of 187 trials (9%) were discarded, either because the jump occurred before the movement started or because participants took more than 800 ms to complete the trial. Table 1 (middle part) shows the total number of trials considered in the analysis for each of the participants in this experiment. One of the participants

Table 2

Average kinematic measures (and between subject Standard Errors of the Mean) for the three Experiments.

	Gap-target task			Two-targets task		
	Movement time (ms)	Peak velocity (cm/s)	Prop. of time to peak velocity (%)	Movement time (ms)	Peak velocity (cm/s)	Prop. of time to peak velocity (%)
Static	541 (24)	122 (6.3)	55 (3.1)	549 (24)	123 (8.3)	53 (3)
1st object upwards	569 (23)	117 (5.5)	52 (3.8)	567 (25)	118 (7.2)	54 (4.4)
1st object downwards	574 (24)	118 (4.5)	50 (2.1)	570 (24)	122 (7.5)	49 (1.9)
2nd object upwards	562 (27)	118 (6.3)	50 (2.1)	573 (25)	119 (7)	50 (2.3)
2nd object downwards	559 (21)	121 (6)	55 (3.4)	556 (25)	123 (8.7)	54 (3.3)
	Two-gaps task			Target-gap task		
	Movement time (ms)	Peak velocity (cm/s)	Prop. of time to peak velocity (%)	Movement time (ms)	Peak velocity (cm/s)	Prop. of time to peak velocity (%)
Static	632 (21)	102 (4.7)	54 (3.6)	606 (21)	108 (5.4)	53 (3.8)
1st object upwards	666 (20)	99 (4.5)	52 (4.7)	635 (23)	108 (5.8)	53 (4.6)
1st object downwards	663 (18)	102 (5.4)	49 (3.2)	628 (22)	108 (5.1)	49 (2.9)
2nd object upwards	656 (21)	101 (5.3)	48 (3.6)	630 (21)	105 (4.9)	49 (3.2)
2nd object downwards	655 (19)	103 (5.5)	53 (4.1)	628 (21)	108 (5.5)	52 (4)
	Control: Two-gaps task			Control: Two-targets task		
	Movement time (ms)	Peak velocity (cm/s)	Prop. of time to peak velocity (%)	Movement time (ms)	Peak velocity (cm/s)	Prop. of time to peak velocity (%)
Static	599 (42)	112 (8.8)	50 (5.1)	598 (45)	108 (11.6)	49 (5.5)
1st object upwards	641 (49)	101 (8.8)	45 (5.1)	609 (33)	108 (9.3)	48 (6.4)
1st object downwards	624 (64)	103 (9.9)	47 (5.2)	628 (44)	109 (12.4)	47 (4.1)
2nd object upwards	597 (47)	109 (4.4)	44 (4.3)	616 (39)	110 (12.7)	46 (4.7)
2nd object downwards	612 (38)	113 (10.3)	48 (5.6)	615 (46)	106 (11.9)	50 (5.7)

(S. 11) seemed to often wait for the jump before starting the movement, so a higher proportion of trials was eliminated. This participant's performance in the remaining trials did not differ from that of the other participants.

4.2.1. Movement characteristics

Table 2 (central part) summarizes the average values of the kinematic variables for each configuration and kind of perturbation. The statistical analysis showed a significant effect of *configuration* (two levels) for total movement duration ($F_{(1,9)} = 7.602$, $p = 0.02$), but not for peak velocity ($F_{(1,9)} = 4.502$, $p = 0.063$) or proportion of time to peak velocity ($F_{(1,9)} = 0.077$, $p = 0.788$). On average, hand movements in the *Target-Gap* configuration had a shorter duration than hand movements in the *Two-Gaps* configuration (see Table 2). We also found significant effects of *perturbation* (five levels) for total duration of movement ($F_{(4,36)} = 7.16$, $p < 0.001$) and proportion of time to peak velocity ($F_{(1,644,14,794)} = 4.119$, $p = 0.044$), but not for peak velocity ($F_{(4,36)} = 0.748$, $p = 0.566$). Static trials had significantly shorter durations than trials with jumps (see Table 2). The proportion of time to peak velocity varied across the different perturbation conditions (see Table 2). None of the interactions reached significance for any of the kinematic variables considered.

Again, there were errors in less than 1% of the static trials (Table 3, central part), while there were errors in a much higher percentage of jump trials (Fig. 2). Paired samples *t*-tests showed a significant difference between average error rates when the first object jumped (gap versus target: $t_{(9)} = 3.019$, $p = 0.014$), but not when the second object jumped (gap versus gap: $t_{(9)} = -1.769$, $p = 0.111$). Moreover, again the highest percentage of errors occurred in trials in which a gap jumped (red bars in Fig. 2). Participants often hit one of the second pair of obstacles in trials

in which the first object jumped (Table 3). Individual differences in general performance can be seen in Table 1. In summary, going through two gaps sequentially was harder than passing through a target first and a gap second.

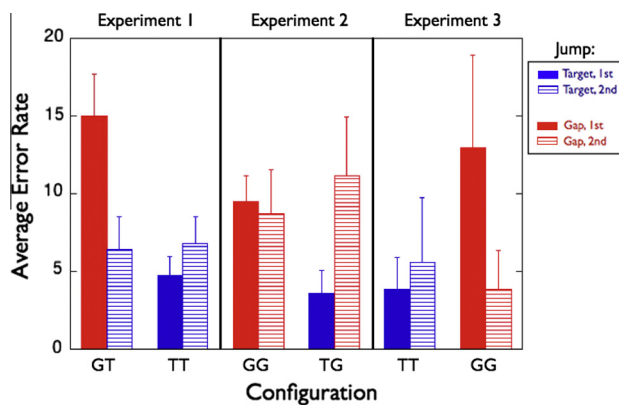
4.2.2. Differences between conditions

Fig. 4 presents the main results of Experiment 2. As in Experiment 1, the response to a jump of the first object on the hand's path was faster when the first object was a target (Fig. 4F, blue curve) than when it was a gap (Fig. 4C, red continuous curve). On average, the response started 113 ms (SEM = 3.3) after a target jump, and 157.5 ms (SEM = 5.8) after a gap jump at the same location (Table 1). The main response to a jump of the second object (always a gap) occurred later than the response to a jump of the first object. The differences between the response onsets in the two configurations varied across participants (Table 1 and bottom parts of Fig. 4C and F). We found a significant difference between the average latencies both when the first object jumped (gap versus target: $t_{(9)} = 7.743$, $p < 0.001$) and when the second object jumped (gap versus gap: $t_{(9)} = 2.801$, $p = 0.021$). For the first object, the response seemed to take about 45 ms longer when a gap jumped than when a target did so. For the second object (always a gap) the response onset time was very variable across participants. The vertical lines indicating when the hand had reached the positions of the objects in 50% of the trials (Fig. 4C and F) and the movement times and velocities (Table 2) suggest that our participants compensated for the longer response times for gaps by slowing down their movements. The pattern in the lateral velocity profiles is similar to that in Experiment 1, but participants moved slightly less fast (Fig. 4B and E). In summary, the difference in response between the two configurations confirms that, even

Table 3

Average error rates (and between subject Standard Errors of the Mean) for each of the experimental conditions of the three Experiments.

	Gap-target task		Two-targets task	
	Obstacle hits (%)	Target misses (%)	Target 1 misses (%)	Target 2 misses (%)
Static	0	0	0	0.5 (0.5)
1st object upwards	14 (4)	3 (2)	5 (2)	3 (1)
1st object downwards	15 (3)	9 (4)	4 (2)	12 (3)
2nd object upwards	0.5 (0.5)	8 (3)	0.7 (1)	10 (3)
2nd object downwards	2 (1)	5 (3)	0	4 (2)
	Two-gaps task		Target-gap task	
	Obstacle 1 hits (%)	Obstacle 2 hits (%)	Target misses (%)	Obstacle hits (%)
Static	0	0	0	1 (1)
1st object upwards	9 (3)	3 (1)	6 (3)	2 (1)
1st object downwards	9 (2)	11 (5)	1 (1)	11 (4)
2nd object upwards	0.5 (0.5)	13 (5)	0	19 (7)
2nd object downwards	0	4 (2)	0.5 (0.5)	3 (2)
	Control: Two-gaps task		Two-targets task	
	Obstacle 1 hits (%)	Obstacle 2 hits (%)	Target 1 misses (%)	Target 2 misses (%)
Static	1 (1)	3 (1)	0	0
1st object upwards	15 (12)	1 (1)	3 (3)	5 (5)
1st object downwards	10 (5)	9 (7)	4 (3)	5 (5)
2nd object upwards	0	7 (4)	0	8 (8)
2nd object downwards	0	0	0	3 (3)

**Fig. 2.** Performance in jump trials. The plot presents the average error rate (with standard errors across subjects) in the three experiments when each kind of target or gap jumped in each of the four configurations: *Gap-Target* (GT), *Two-Targets* (TT), *Two-Gaps* (GG) and *Target-Gap* (TG).

when they impose the same kinematic constraints and occupy the same positions with respect to the hand's trajectory, targets and obstacles are dealt with differently.

4.3. Discussion

In Experiment 2 we compared hand movement performance in two configurations: *Two-Gaps* and *Target-Gap* (bottom part of Fig. 1). Again, the main comparison was between the times taken to respond to the first object jumping when that object was either a target or a gap, and again the second object was always the same although it was now always a gap whereas in Experiment 1 it was always a target. The results were very similar to those of Experiment 1. Participants corrected their hands' trajectories in response to the displacements of both kinds of objects (Fig. 4A and D) and did so quickly enough to avoid hitting the obstacles or missing the targets excessively (Fig. 2). The kinematics of the movements changed when the objects jumped, and again we found a systematic difference in response times between targets and gaps. When the first object on the hand's path was a target that jumped, the average response was 45 ms faster than when the first object on

the hand's path was a gap that jumped in the same manner (Fig. 4C and F, Table 1). We will discuss this result in relation to the results of the other two experiments in section 6.

5. Experiment 3 (control)

In Experiments 1 and 2 we found that participants responded faster when a target jumped than when a gap jumped at the same location. Since targets were always white and obstacles were always red we decided to perform a final control experiment to make sure that the effects that we found did not depend on the objects' colors. Although color may seem to be an irrelevant property in terms of motor control, there are results that suggest that chromatic differences between targets and irrelevant objects can influence movement execution (Gentilucci et al., 2001). Moreover, the white target had a higher luminance contrast with the background than the red obstacles, and luminance contrast is known to influence the response time (Brenner & Smeets, 2003; Veerman, Brenner, & Smeets, 2008). To make sure that our effects did not depend on the colors chosen for targets and obstacles, we performed a control experiment in which we interchanged the colors of the stimuli (red targets and white obstacles) and tested two of the four previous configurations with a smaller group of participants. The experimental procedures were similar to those used in Experiments 1 and 2.

5.1. Methods

5.1.1. Participants

Four of the participants of Experiment 2 (including two of the authors) voluntarily took part in this control experiment (2 males and 2 females, ages ranging from 23 to 53).

5.1.2. Stimuli

Again, only two of the four possible configurations were presented: *Two-Gaps* and *Two-Targets* (second and third rows in Fig. 1). The colors of the objects were interchanged with respect to experiments 1 and 2: the *two gaps* were formed by pairs of large white rectangles and the *two targets* were red.

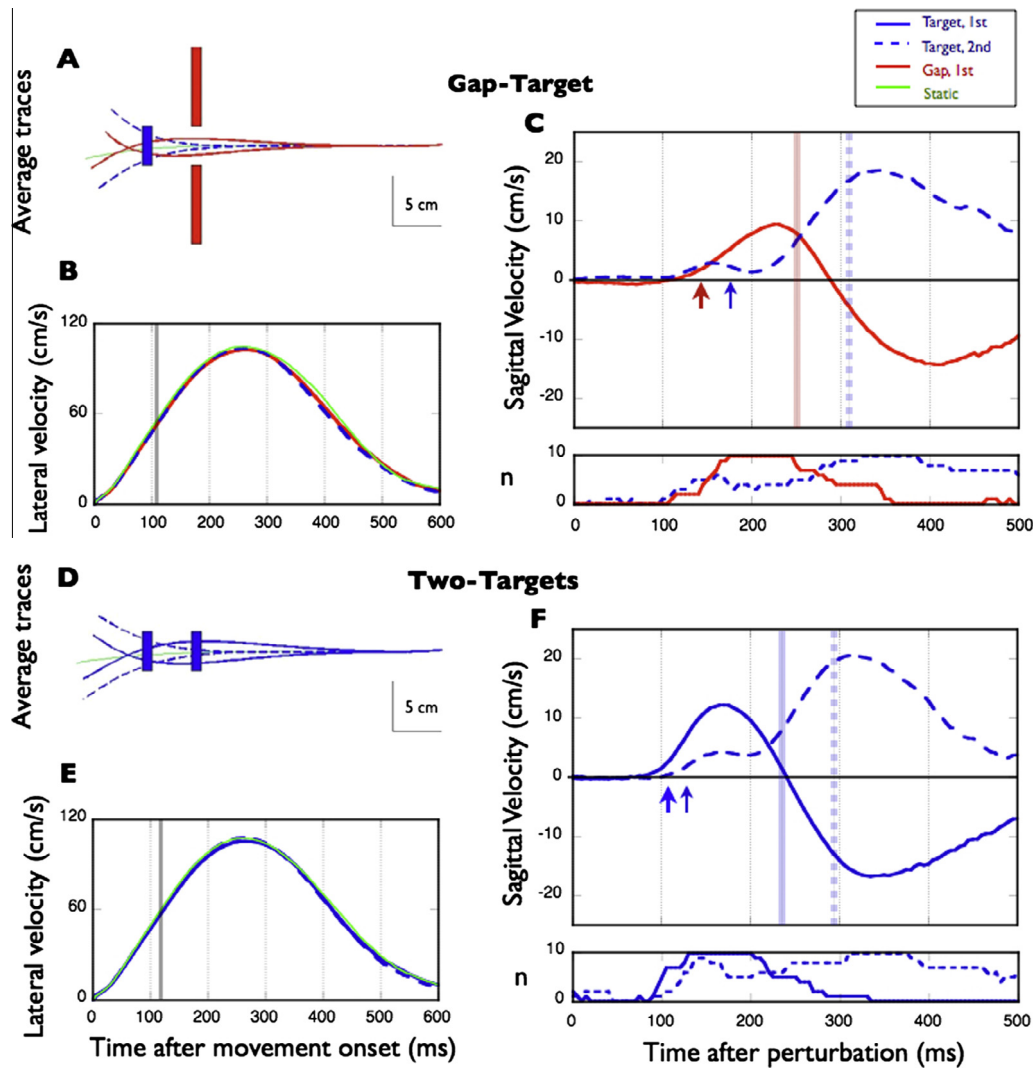


Fig. 3. Results for the two configurations of Experiment 1. *A and D:* Average movement paths for each kind and direction of perturbation. *B and E:* lateral velocity profiles for each kind of perturbation. These velocity profiles are synchronized at movement onset and averaged across the two jump directions. The grey translucent lines indicate the average time of the jumps. *C and F:* Average sagittal velocity and number of participants (*n*) for whom the hand's velocity was significantly different for the two jump directions, as a function of time after the moment at which the jump occurred. For trials with downward jumps, the sign of the sagittal velocity was reversed before averaging. To relate the time at which the responses to the jumps occurred with the hand's position on its trajectory, translucent vertical lines indicate the time at which the hand has passed each object on 50% of the trials. Arrows indicate the average of the subjects' individual response latencies (see also Fig. 6).

5.2. Results

A total of 159 trials (19%) were discarded either because the jump occurred before the movement started or because participants took more than 800 ms to complete the trial. Table 1 (lower part) shows the total number of trials considered in the analysis for each of the participants in this experiment. One of the participants (S. 11) seemed to often wait for the jump before starting the movement, so a higher proportion of trials was eliminated. This participant's performance in the remaining trials did not differ from that of the other participants.

5.2.1. Movement characteristics

Table 2 (bottom part) summarizes the average values of each of the kinematic variables for each configuration and perturbation. Given the small sample size in this experiment (4 participants) we did not perform any statistics on the data. As in the previous experiments, movements seemed to be slower when there was a perturbation (see Table 2, bottom part). Lateral velocity profiles were bell shaped (Fig. 5B and E).

There were no errors in the *Two-Targets* trials in which neither target jumped (see Table 3, lower part). There were errors in 1% and 2% of *Two-Gaps* trials in which neither gap jumped. The error rate in trials with jumps was much higher, as can be seen in Fig. 2. The highest percentage of errors (15%, SEM = 11%) occurred in trials in which a gap at the first location jumped. Participants occasionally hit one of the second obstacles or missed the second target in trials in which the first object jumped (Table 3). Individual differences in the average error rate can be seen in Table 1.

5.2.2. Differences between conditions

Fig. 5 presents the main results of Experiment 3. On average, the response started 126.2 ms (SEM = 2.7) after a target jump at the first location, and 158.7 ms (SEM = 2.7) after a gap jump at the same location (Table 1). Responses to a target jumping (*Two-Targets*) were on average 32 ms faster than responses to a gap jumping (*Two-Gaps*). All participants responded substantially faster to a target jump at the first location than to a gap jump at that same location (Fig. 5C and F, also see Table 1). With respect to the second object on the hand's path we can see that when it was a target

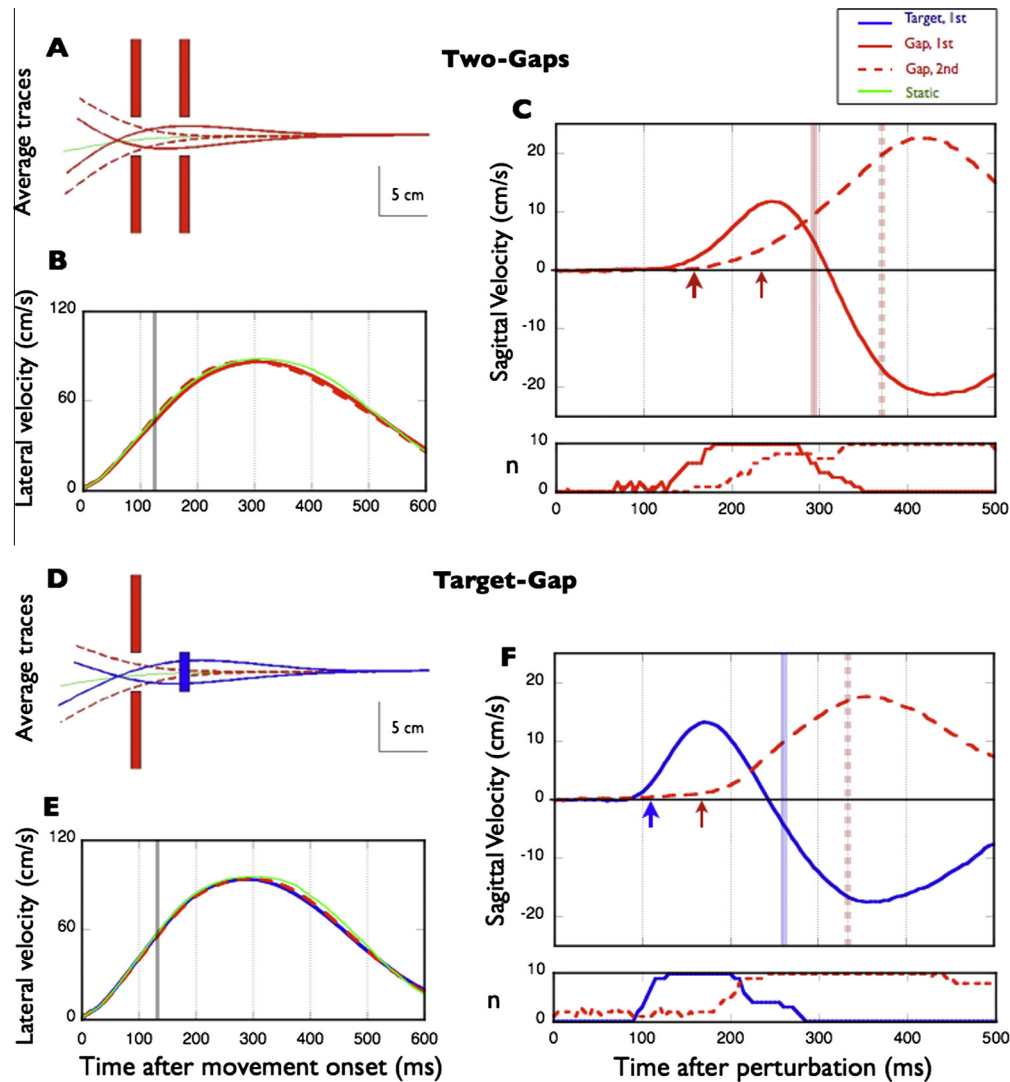


Fig. 4. Results for the two configurations of Experiment 2. See Fig. 3 for further details.

(*Two-Targets configuration*) there was an early response that coincided with the response when the first target jumped. When the second object in the path was a gap (*Two-Gaps configuration*), there was no such early response. This distinction can also be seen by comparing Figs. 3C and 4C. Again the lateral velocity profiles were very similar for perturbed and unperturbed trials, although looking at all the lateral velocity profiles (in Figs. 3–5B and E) we see a tendency for the lateral velocity to be lower from about 200 ms after the perturbations than when there was no perturbation (green curves above others), which is consistent with the hand slowing down a bit in response to the perturbation (as we saw from the movement times). The main conclusion that we can draw from Experiment 3 is that the difference in color between targets and obstacles in experiments 1 and 2 is not responsible for the faster response to target jumps. We will discuss these results further, together with the results of the other two experiments, in the next section.

6. Comparison of the three experiments

The results of the three experiments were very similar: in all cases we found a clear difference between the latency to respond to a target jump and the latency to respond to a similar jump of the gap. Fig. 6 presents the average latency of the hand's corrective

response for displacements of each object in all conditions of all three experiments. For the *first* object located on the hand's path, the response to a jump was faster when it was a target than when it was a gap between two obstacles, irrespective of the characteristics of the second object. Across participants, and taking the conservative estimate given by the moment the *t*-tests were significant, the average response onset time for a target jump was 113 ms. The average response onset time when a gap jumped was about 155 ms.

For the *second* object on the hand's path, the response onset time depended on the identity of the first object (it was longer if the first object was a gap). The identity of the first object probably influences the moment during the movement at which the second object starts being considered. This probably also differs between participants, because these response onset times were also more variable across participants. However, here too we found slower responses to jumps of gaps than of targets. If the first object was a target, the average response onset time was 135 ms when a target in the second position jumped (*Two-Targets configuration*) and 171 ms when a gap in the second position jumped (*Target-Gap configuration*). If the first object was a gap, the average response onset time was 186 ms when a target in the second position jumped (*Gap-Target configuration*) and 237 ms when a gap in the second position jumped (*Two-Gaps configuration*).

One very interesting observation is that target jumps at the second location (*Two-Targets* and *Gap-Target* configurations) produced two apparent peaks in the sagittal response profiles, instead of just one (see blue dotted lines in Figs. 3C and F and 5F). The initial response to the second target jumping appears to have been as fast as the response to the first target jumping, but to have quickly been suppressed until the first object was passed. When the second object on the path was a gap there was no evidence of such suppression, although the response to the gap jumping also started before the hand passed the first object. This finding supports the notion that targets and gaps are treated differently. It also points to a limit on the kind of objects that can produce an automatic capture of the hand, as we will discuss in the next section.

Although all the configurations in our experiments were designed to be the same in terms of kinematic constraints, there is one aspect in which there could be a difference. To successfully intercept a target it does not matter how the hand passes the target. However, previous research on obstacles suggests that people make sure that their hand or fingers do not come too close to the obstacle (Biegstraaten, Smeets, & Brenner, 2003; Chapman & Goodale, 2008, 2010a, 2010b; Dean & Brüwer, 1994; Jackson, Jackson, & Rosicky, 1995; Mon-Williams et al., 2001; Sabes & Jordan, 1997; Saling et al., 1998; Tresilian, 1998; Voudouris, Smeets, & Brenner, 2012). Finding the optimal trajectory to pass through the gaps in our experiments may therefore be considered

to be more restrictive in terms of movement constraints than just reaching a target, although in terms of the true requirements that we implemented it is not. If so, we would expect to find less variability in where the hand passes the gap than in where it passes the target. For each trial, we therefore determined the sagittal hand position when passing each of the presented objects. We averaged

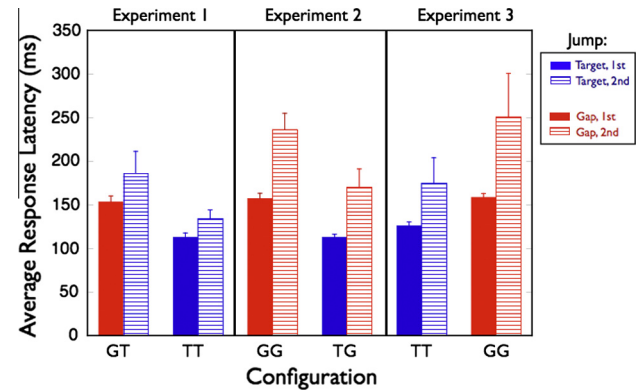


Fig. 6. Average response latencies in all three experiments. The bars present the average latency of the hand's response when each kind of target or gap jumped (with standard errors across subjects). Configurations: *Gap-Target* (GT), *Two-Targets* (TT), *Two-Gaps* (GG) and *Target-Gap* (TG).

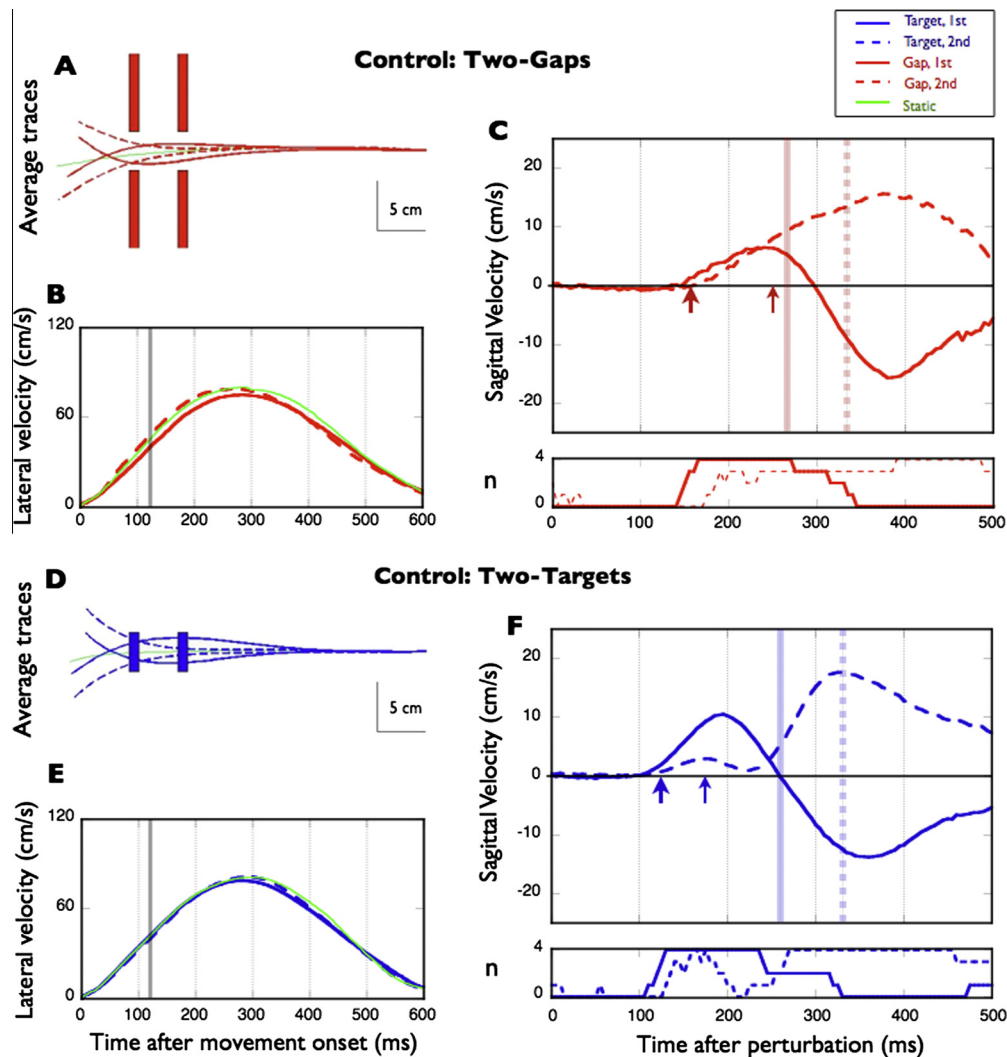


Fig. 5. Results for the two configurations of Experiment 3. See Fig. 3 for further details.

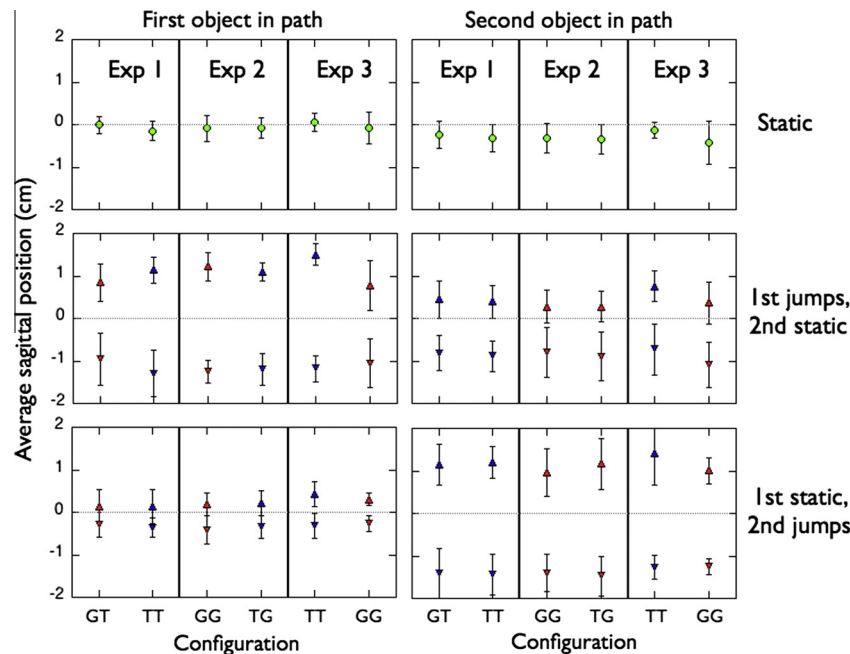


Fig. 7. Average sagittal position when passing the *first object* (left) and the *second object* (right) along the path in each configuration. Upper part: *static trials*. Middle part: *first object jumps*. Bottom part: *second object jumps*. Upward and downward pointing triangles indicate jumps away from and towards the participant. Red and blue indicate gap and target, respectively. The line at zero corresponds to the center of the object when static. After a jump, the center of the object is at $y = 2$ cm for jumps away from and at $y = -2$ cm for jumps towards the participant. In those cases (middle left and bottom right) one edge of an obstacle is at zero. Error bars represent the overall standard deviation of the sagittal position.

these sagittal positions for each direction of the jump in each configuration tested, and related the mean position to the center of the target or gap. We also determined the standard deviations in these positions for each direction of the jump in each configuration tested. We expected to see average values closer to the center and smaller standard deviations when the object was a gap than when it was a target. The values for the static objects in Fig. 7 shows that there was no such effect, neither for the first nor the second object in the path, which does not support the proposal that the constraints are considered to be different.

Fig. 7 also clearly shows that after an object jumps participants do not pass through the center of the displaced object. When an object jumps they do not pass through the center of the *other* object in the path either. This is probably because they do not have enough time to fully adjust to the jumps. They could have slowed down to do so, risking being told that they had moved too slowly, but passing about 1 cm from the object's center was enough to be successful on most trials. When the first object was a target that jumped, it was missed on at most 6% of the trials (Table 3). When the first object was a gap that jumped, the obstacles were hit on between 9% and 15% of the trials. Similarly, when the second object on the path jumped, between 3% and 10% of the targets were missed, whereas obstacles were hit on up to 19% of the trials. On average participants moved too slowly on only 1.6% of the trials. These differences are consistent with the idea that responses are faster when targets than when obstacles are perturbed during goal-directed hand movements.

7. General discussion

In a series of three experiments we compared participants' performance in four different configurations that were precisely matched in terms of the physical movement requirements. These configurations required a hand movement passing through two objects (either targets or gaps) that could jump to a new location

after the movement had started. The only difference between the four configurations was in the combination of objects that were presented visually (Fig. 1). The results of the three experiments were very similar. In all cases, participants corrected their trajectories in response to the jumps, as is evident from the average trajectories (Figs. 3–5A and D), as well as from the hand, on average, missing the target or hitting the obstacles on less than 15% of the trials (Fig. 2). Most importantly, in all experiments we found a clear, statistically significant difference between the latency to respond to a target displacement and the latency to respond to the displacement of a gap between two obstacles (Fig. 6). These results confirm our previous observation (Aivar, Brenner, & Smeets, 2008) that targets and obstacles are not treated in the same way when controlling hand movements.

Why do responses to displacements of a gap take longer than those to displacements of a target? One reason may be that it is less certain that one should respond to motion of an obstacle. Many studies have shown that having other objects near a target can influence hand movements towards that target even if they are completely irrelevant to the movement. Such distracters have been reported to influence reaction time and movement duration (Keulen et al., 2004; Meegan & Tipper, 1998; Pratt & Abrams, 1994; Tipper, Lortie, & Baylis, 1992; Tipper, Howard, & Jackson, 1997). They have also been reported to "attract" the hand (Chang & Abrams, 2004; Sailer et al., 2002; Welsh, Elliott, & Weeks, 1999) as well as to "repel" the hand (Fischer & Adam, 2001; Gangitano, Daprati, & Gentilucci, 1998; Howard & Tipper, 1997; Tipper, Howard, & Jackson, 1997) or have no influence on the hand (Castiello, 1996; Chieffi et al., 1993). Similarly, variable results have been found for eye movements (for a general review on the effects of distracters on saccade trajectories see: van der Stigchel, Meeter, & Theeuwes, 2006; van der Stigchel & Theeuwes, 2005). Part of the problem may be that the distinction between (irrelevant) distracters and (relevant) obstacles is not clear, so they may be confused depending on how the task is designed and presented (Tresilian, 1999). However, in our experiments it was clear

that the objects that were not targets were obstacles, rather than distracters, so it was obvious that it was essential to attend to both these kinds of objects.

There are, of course, visual differences between targets and gaps. There must be, because if targets and obstacles were identical we would not be able to distinguish between them. In this study, we equated the motor constraints, so the results show that motor constraints are not responsible for the difference in latency between responses to targets and obstacles. We know that the fact that the gap consisted of two obstacles, whereas we only had one target, is not responsible for the difference in latency, because in our previous study we also found longer latencies for a single obstacle than for a target (Experiment 2 of Aivar, Brenner, & Smeets, 2008). Whether the way movements are controlled differs for obstacles and targets, or whether the difference is mediated by some other factor such as where gaze is directed, remains to be examined. We speculate that the difference may have to do with the obstacles being treated as regions that must be avoided, so the whole obstacle has to be considered, whereas a specific point on the target can be selected to guide the movement (Verheij, Brenner & Smeets, 2012). However, it is not evident that this difference should result in a difference in latency.

Comparing Figs. 3–5, we see early peaks in the sagittal velocity profiles when a target at the second position jumped (3C, 3F and 5F), but not when a gap at the second position jumped (4C, 4F and 5C). That an early response is only suppressed for target jumps could result from the fact that responses to gaps had a longer latency, so that the hand was closer to passing the first object by the time the adjustment occurred. This might have made it less important to suppress a response to a gap at the second position jumping, if it occurred. However, the sagittal velocity before reaching the first object is not negligible in these trials (compare dashed red curves with solid vertical lines in Figs. 4C and 5C), and it is far from evident that counterproductive responses can be inhibited (Aivar, Brenner, & Smeets, 2008; Day & Lyon, 2000; Oostwoud Wijdenes, Brenner, & Smeets, 2011; Pisella et al., 2000), so there may be more to the difference between targets and obstacles.

Automatic responses are observed when relevant structures such as the target of the movement (Brenner & Smeets, 1997; Oostwoud Wijdenes, Brenner, & Smeets, 2011; Prablanc & Martin, 1992; Soechting & Lacquaniti, 1983) or obstacles (Aivar, Brenner, & Smeets, 2008) are displaced, but global motion of irrelevant items in the visual field also automatically attracts the hand (Brenner & Smeets, 1997; Saijo et al., 2005; Whitney, Westwood, & Goodale, 2003). Perhaps the fact that all objects in the visual field that could be relevant for the movement are considered as potential obstacles (Chapman & Goodale, 2010b) delays the response to obstacles because the presence of more objects decreases the automatic capture of the hand (Cameron et al., 2007). Thus, the precise reason for the difference in latency between responding to targets and obstacles is not clear, but it is clear that the responses to perturbations of targets and obstacles are different, even when there is no biomechanical reason for them to be so.

Acknowledgments

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