

## Missing in action: the effect of obstacle position and size on avoidance while reaching

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**Abstract** When reaching to objects, our hand and arm rarely collide with non-target objects, even if our workspace is cluttered. The simplicity of these actions hides what must be a relatively sophisticated obstacle avoidance system. Recent studies on patients with optic ataxia and visual form agnosia have demonstrated that obstacle avoidance is an automatic process, likely governed by the dorsal stream (Schindler et al. 2004; Rice et al. 2006). The current study sought to quantify how normal participants react to changes in the size and position of non-target objects in and around their workspace. In the first experiment, 13 right-handed subjects performed reaches to a target strip in the presence of two non-target objects, which varied in depth and horizontal configuration. We found that objects with horizontal alignments that were asymmetric about midline created systematic deviations in reach trajectory away from midline, with participants seeming to maximize the distance away from the two objects. These deviations were significantly greater for objects nearer in depth and nearly disappeared when the objects were placed beyond the target strip. Accompanying this pattern of deviation were other significant obstructing effects whereby reaches were executed more slowly when objects were close in depth and close to the participants reaching (right) hand. In the second experiment, we varied the height of the two objects, as well

as the depth. Object pairs were now both tall, both short, or one-short/one-tall. We replicated the significant depth effects of the first experiment, extending the finding to include sensitivity to the size of the objects. Here the obstructing effect caused by short objects was similar to tall objects when those objects were placed at the depth of the reach target, but less than the tall objects when placed at mid-reach. Taken together, these experiments suggest that humans possess a sophisticated obstacle avoidance system that is extremely sensitive and conservative in evaluating potential obstacles and adjusting the reach accordingly.

**Keywords** Obstacle avoidance · Reaching · Visuomotor control · Planning · Human

### Introduction

When making reaches our hand and arm rarely make contact with non-target objects, suggesting that a sophisticated system must exist to encode possible obstructions to a reach and incorporate them into motor plans and execution. Behavioral experiments have confirmed the existence of such a system, showing that the introduction of non-target objects into the workspace alters the spatial and temporal trajectories of reaching and grasping (e.g. Castiello 1996; Howard and Tipper 1997; Jackson et al. 1995; Tipper et al. 1997; Tresilian 1998). While the effects of non-target objects can be explained under a number of theoretical frameworks, for simplicity we will refer to this ability as obstacle avoidance, and return to a discussion of the mechanism of interference later.

The apparently ‘automatic’ nature of obstacle avoidance suggests that the mechanisms underlying its control may involve relatively encapsulated visuomotor systems. Recent

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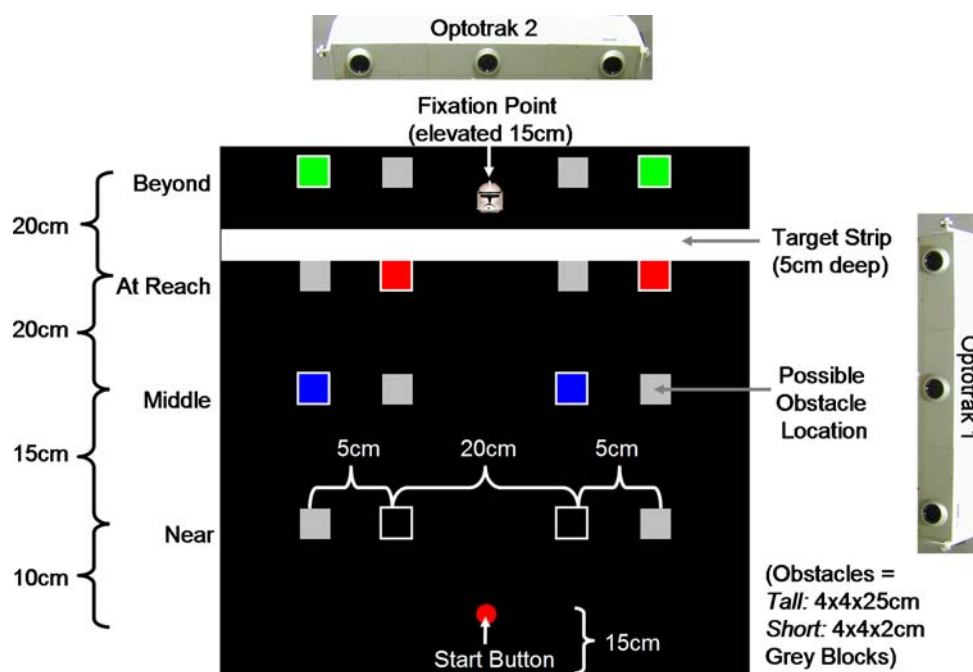
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work with various patient populations has shed light onto possible neural substrates for this behavior. Given the substantial evidence demonstrating the critical role that dorsal-stream structures play in visually guided action (e.g. Goodale and Milner 1992; Goodale et al. 1991; James et al. 2003; Milner et al. 1991; Perenin and Vighetto 1988; Rossetti et al. 2005), it is not surprising that successful obstacle avoidance also seems to require an intact dorsal stream (McIntosh et al. 2004a, b; Milner and McIntosh 2004; Rice et al. 2006; Schindler et al. 2004). Each of the obstacle avoidance studies with patients used a similar paradigm, having patients and control participants perform a simple reaching or bisection task in the presence of two non-target objects whose horizontal position varied. The changes in object position resulted in four different configurations, two in which the objects were the same distance from midline (symmetrical) and two in which the objects were different distances from midline (asymmetrical, see Fig. 1). In the bisection task, patients and participants were instructed to take as much time as needed to point to the mid-point between the two objects and in the reaching task, they were instructed to reach quickly between the two objects to a target strip located beyond the objects. These different task demands meant that the bisection task

required explicit attention to the two objects while the reach task did not. In a first set of studies, researchers examined the performance of patients with neglect in the above experimental conditions (McIntosh et al. 2004a, b; Milner and McIntosh 2004). In the reach task, the majority of patients with neglect performed similarly to control participants, deviating their reaches away from midline when the objects were placed in an asymmetrical configuration, as though they were avoiding the object closer to midline. In the bisection task, however, patients with neglect seemed insensitive to the position of the left object when making midpoint judgments. In a further study testing a patient with extinction, McIntosh and colleagues demonstrated that reaching movements deviated to avoid obstacles even when the presence of the obstacle did not reach visual awareness (McIntosh et al. 2004a, b; Milner and McIntosh 2004). The preserved avoidance ability in patients with neglect or extinction was attributed to their preserved dorsal-stream processing. In contrast, Schindler et al. (2004) found that patients with optic ataxia behaved differently on the same task. In this study, two optic ataxic patients performed similarly to controls on the bisection task but showed no evidence of obstacle avoidance in the reaching task. That is, when making reaches to the target



**Fig. 1** Experimental setup for experiment 1. Participants made reaches from the start button to the target strip while fixating on an elevated fixation point, all of which were on a 1 m x 1 m black fabric board. When obstacles (4 cm<sup>2</sup> base, 25 cm tall) were present, one was to either side of midline at the same depth. All possible obstacle locations are shown (*squares*), indicating they could appear at four depths and in four configurations: depths = near (9 cm), middle (24 cm), at reach (44 cm), beyond (64 cm); configurations = both-in (*black*), left-out (*blue*),

both-out (*green*), right-out (*red*). Note these configurations are the same as used in the patient studies (e.g. Schindler et al. 2004). Movements were recorded using two OPTOTRAK cameras (one right, one in front) at 100 Hz. Setup for experiment 2 was identical except for the removal of the near depth and both-out configuration, and the inclusion of trials with different sizes of objects (tall same as described above or short, 4 cm<sup>2</sup> base, 2 cm tall)

strip, the patients with optic ataxia tended to follow the same trajectory, regardless of object configuration. That the bisection performance of these patients is intact while the avoidance behavior is impaired again suggests that the dorsal stream is critical to successful avoidance. Finally, using the same avoidance paradigm, experimenters have looked at the performance of patients with visual form agnosia from damage to ventral-stream structures (Rice et al. 2006). These patients, who have largely intact dorsal-stream processing, show impaired bisection performance and preserved avoidance behavior in the reach task. Thus, patients with visual form agnosia are similar to neglect patients in their relatively poor bisection and good avoidance and provide an important contrast to the patients with optic ataxia. All of these studies suggest that the dorsal stream plays a critical role in avoidance behavior.

The aim of the current study was to explore systematically the factors contributing to obstacle avoidance behavior in neurologically intact participants in the same paradigm that has been so often used in the patient work. By using and extending the paradigm used with patients, we are confident that we are investigating a behavior with known neural substrates. Having evidence of where in the brain obstacles are being encoded, however, does little to explain how these brain areas use this information to allow us to avoid obstacles while reaching.

There are at least three potential explanations that have been put forward to account for the observed effects of non-target objects on reaching behavior: non-target objects functioning as distractors (e.g. Castiello 1996, 1999, 2001; Tipper et al. 1992, 1997; Tipper et al. 2002), non-target objects functioning as landmarks (Bridgeman et al. 1997; Diedrichsen et al. 2004; Obhi and Goodale 2005), and non-target objects functioning as obstacles (Mon-Williams et al. 2001; Tresilian 1998, 1999; Tresilian et al. 2005). In the task we used, which was adapted from the earlier patient work, the non-target objects were much more likely to be treated as obstacles than as distractors or landmarks. First, participants were instructed to perform their reaches as quickly and accurately as possible and to ignore the non-target objects. Under these conditions, it is unlikely that the non-target objects were ever coded as potential targets—that is, their ‘relative salience’ (Tipper et al. 2002) was extremely low. Second, their role as landmarks was also diminished since their position varied from trial to trial—and, even on a single trial, the target position was not fixed with respect to the non-target objects. In short, the behavior observed in the current experiment was almost certainly due to obstacle avoidance.

The obstacle avoidance account of the effects of non-target objects was put forward by Tresilian (1999, 1998). According to his model, interference from non-target objects during a reach-to-grasp movement, namely slower

reaches and deviations away from the non-target objects, is explained as an automatic adjustment of the movement that minimizes the risk of colliding with the obstructing objects. In his original study, Tresilian (1998) was specifically arguing against the distractor account, and did so by showing different obstructing effects for the same configuration of target and non-target objects when all that changed was the wrist posture of the participant. That is, with one wrist posture (extended) the orientation of the grasping digits caused a non-target object beside the target object to obstruct the movement, while the other wrist posture (flexed) meant the grasping digits were not obstructed by a non-target object to the side of the target. Tresilian reasoned that the distractor account would not predict differences in non-target interference due to a change in wrist posture. In a follow-up study, Mon-Williams et al. (2001) carried out a more thorough exploration of the effect of obstacle position and size on reach-to-grasp movements. In this study, obstacles (alone or in pairs) were placed in one of four positions in close proximity to a target block. The obstacles could be tall or short, but the experimenters found no consistent effects due to obstacle size. All the potential obstacle positions were clustered around the target object, however, because the researchers were primarily interested in the effects of such obstacles on the grasp component of the reach-to-grasp movement. Mon-Williams et al. concluded that movement plans are conservative when taking account of obstacles, slowing the reach and altering the grip aperture in a manner that varies with the degree to which obstacles constrain a given movement.

The Tresilian (1998) and Mon-Williams (2001) studies highlight one of the strengths of the obstacle-avoidance account—that is, its ability to explain the close relationship between adjustments in the movements made by the participant and the degree to which the non-target objects actually obstruct those movements. In the current study, we wanted to build on this theme and vary the amount a non-target object obstructed a reaching movement by changing the object’s position and size and measuring its impact on reach trajectories. By its nature, the paradigm we adapted from the patient literature allows us to explore a wider range of obstacle positions encompassing the majority of the workspace (see Fig. 1). In doing so, we hoped to extend the previous work of Mon-Williams et al. (2001) and examine the effects of obstacles placed throughout the workspace on the transport phase of a reach-to-point movement. Thus, in the first experiment, we varied not only the horizontal configuration of two tall non-target objects through which participants reached (the only manipulation used in the patient work), but also the depth at which the objects were placed (see Fig. 1). In some cases, the non-target objects were placed past the reach target, and, despite being clearly visible, offered no obstruction to the reach movement. In

the second experiment, in addition to the depth, we varied the size of the non-target objects such that one or both could be tall or short. As mentioned earlier, Mon-Williams et al. (2001) reported no effect of obstacle height on reach-to-grasp movements. However, by substantially decreasing the height of the objects, especially when placed mid-reach, we significantly reduced the amount these objects obstructed the reach movement, and thus we predicted an effect of size in this experiment. Thus, by using a larger range of obstacle positions and sizes, the current study was able to examine in greater detail how neurologically intact participants perform in the obstacle avoidance paradigm that has been previously used with patients.

## Experiment 1

### Materials and methods

#### *Participants*

A group of 13 right-handed (determined by self-report) adults (5 males) were included in this study. All participants had normal or normal-to-corrected vision and all participants were naïve to the purpose of the experiment. The present study is part of ongoing research that has been approved by the Local Ethics Committee.

#### *Materials and design*

Participants sat in front of a 1 m × 1 m table covered in black fabric with a horizontally centered start button 15 cm from the front edge of the table, and a target strip of white tape running across the entire width of the table at a distance of 45–50 cm away from the start button. A horizontally centered fixation point, 50 cm away from the start button was elevated 15 cm above the table on a thin pole (see Fig. 1). Participants wore PLATO LCD goggles and had OPTOTRAK infrared markers (IRED) taped to the tip of their right index finger, the base of their right pinky finger, and their right elbow. When recording, the position of each IRED was tracked by two OPTOTRAK cameras at a rate of 100 Hz. Marker wires were held in place with elastic wrist and elbow bands to allow for unrestricted arm movement.

Pairs of tall rectangular objects (4 × 4 × 25 cm with IREDs in the middle of the top facing surface) were placed on the table in one of 17 arrangements (including one where no objects were present), which varied in depth and horizontal configuration. Possible depths: near (front edge 9 cm from start button), middle (24 cm), at reach (44 cm) and beyond (64 cm). Possible configurations: two symmetrical cases: both-in (inside edges 10 cm to either side of mid-

line), and both-out (inside edges 15 cm to either side of midline), and two asymmetrical cases: right-out (left 10 cm, right 15 cm away from midline) and left-out (left 15 cm, right 10 cm away from midline) (see Fig. 1).

#### *Procedure*

Each trial started with participants placing their right index finger on the start button. The goggles were closed, allowing the experimenter to place the objects in one of the above arrangements without the participant seeing the object positions. The trial was triggered by the experimenter, which caused the goggles to open and started the OPTOTRAK recording for 3 s. Participants were instructed to fixate on the fixation point and to execute a reach from the start button to anywhere along the target strip as quickly as possible. They were told that when objects were present, there would always be one on the left and one on the right of midline and that they should pass their hand between them. Other than this instruction, participants were told to ignore the placement of the objects, and focus on performing the reach quickly and accurately. As soon as participants lifted their finger off the start button to initiate their reach, the goggles were closed—thus reaches were performed in visual open loop. Participants completed 8 repetitions of each of the 17 configurations for a total of 136 pseudo-randomly ordered trials.

Before starting the experiment, participants were given practice trials until they reported being comfortable with the timing (always < 10). For the practice trials, objects were presented at the middle depth but further from midline than the both-out configuration.

#### *Data processing*

All analyses were conducted on data from the IRED on the right index finger. Reaches were said to begin with the first of four consecutive vector velocity (i.e. three-dimensional velocity) readings of greater than 20 mm/s where there was a total acceleration of 20 mm/s<sup>2</sup> across the four points. Reaches were said to terminate with whichever of two conditions was first met: the first of three consecutive displacement readings back toward the start button (i.e. three negative displacements in the y-direction) or the first time the velocity dropped below 20 mm/s.

Missing data from an index finger IRED that was temporarily blocked from the view of the OPTOTRAK cameras due to the positioning of the objects was filled in with translated data from the pinky IRED. When both the index and pinky IREDs were missing, the data were linearly interpolated across the missing region. Linear interpolation was required on <4% of trials, and, where required, was interpolated across an average of less than five time points.

Trials were rejected for the following reasons: the reach never reached the minimum velocity, the reach did not terminate within the recording window, the reach was too short in either duration (<100 ms) or distance (<250 mm in depth), or errors in OPTOTRAK recording (usually due to blocked IREDs) caused velocity spikes of >6,000 mm/s. Under these criteria <1% of the trials were rejected.

Reach trajectories were normalized as follows: first, all trajectories were translated such that the first reading of the index finger IRED was taken as the origin of the trajectory (i.e. 0,0,0 in 3D Cartesian space,  $x$  = horizontal,  $y$  = depth,  $z$  = vertical). Second, all trajectories were rotated such that the origin and fixation point (which also had an IRED) were aligned along the  $y$ -axis. Finally, for the lateral and vertical deviation measures, all trajectories were normalized such that they had exactly 100 position measurements, allowing for spatial averaging.

### Dependent measures and analysis

*Reaction time (ms)*: time from the start of the trial to the first frame used as the beginning of the reach movement.

*Movement time (ms)*: measured as the time between reaction time and the last frame of the reach movement.

*Peak velocity (mm/s)*: the highest velocity obtained during the movement time.

*Time to peak velocity (ms)*: the time from the onset of movement until the peak velocity was reached.

*Percent time to peak velocity*: the time to peak velocity expressed as a fraction of the total movement time.

*R-out–L-out area (mm<sup>2</sup>)*: the area between the right-out reach trajectory and left-out reach trajectory was approximated using the trapezoidal method. In brief, the area below (or to the right) of the right-out trajectory was calculated by assuming a line connecting adjacent points in the trajectory and calculating the area of the corresponding trapezoid, with its base on the midline. All trapezoid areas formed from connected points were summed together to get the total area for a given trajectory. The same was done for the left-out curve and the resultant area was subtracted from the right-out area. For simplification both curves were shifted up (or to the right) so all area values would be positive. Since the shift was the same for both the right-out and left-out curves, it was eliminated by the subtraction.

*X@100, X@250, X@450 (mm)*: three measures of horizontal deviation ( $x$ ) were taken, one near the start of the reach [100 mm in depth ( $y$ ) from start button], one near the middle of the reach (250 mm), and one near the end of the reach (450 mm).

*Z@100, Z@250, Z@450 (mm)*: three measures of the absolute vertical deviation ( $z$ ) were taken, at the same three depth ( $y$ ) values as for the horizontal measures.

For each subject, each of the dependent measures was calculated on every trial, then averaged for each of the 17 (depth  $\times$  configuration) arrangements. Each of the dependent measures (except the area measure, and see results section for note on trials with no objects) was then entered into a two-factor depth  $\times$  configuration ( $4 \times 4$ ) repeated-measures ANOVA. For the area measure, a single-factor repeated-measures ANOVA was conducted across the four levels of Depth. Where significant, an interaction of depth and configuration was followed up with simple main effects single-factor ANOVAs of configuration at each depth. Post hoc follow-ups to significant main effects and simple main effects compared all possible pairwise comparisons of the relevant factor (depth or configuration for main effect, configuration for simple main effect). All repeated-measures ANOVAs were analyzed using the Greenhouse-Geisser correction for sphericity and taken to be significant at  $P < 0.05$ . Post hoc pairwise contrasts used the Bonferroni correction for multiple comparisons with a corrected  $P < 0.05$  taken as significant. All measures showing significant effects are reported in Table 1.

### Results

#### *Trials with no objects*

A separate analysis was conducted to compare reaches made when no objects were present versus when objects were present. Specifically, all dependent measures were averaged for reaches made with objects at the middle depth, reaches made with objects at the beyond depth and reaches made with no objects present and compared using a single-factor repeated-measures ANOVA. Reaches with objects placed at the middle depth were longer, slower, and were shifted more to the left (a product of the fact that the right hand was being used, see Fig. 2) as compared to reaches made without objects or with objects placed beyond the target strip. For full statistical analysis of these findings, see Supplementary Table 1.

#### *Temporal effects*

There were no significant main effects or interactions for reaction time, time to peak velocity, or percent time to peak velocity. As shown in Table 1, however, there was a main effect of both depth and configuration for movement time, and a depth  $\times$  configuration interaction for peak velocity. Together with the follow-ups shown in Table 1, these effects indicate that objects close to the participants in depth and on the right-hand side caused longer movements with lower peak velocities. The peak velocity data also show that objects in the both-in configuration still influence the speed of the reach even when placed past the target.



**Table 1** Dependent measures with significant effects in experiment 1

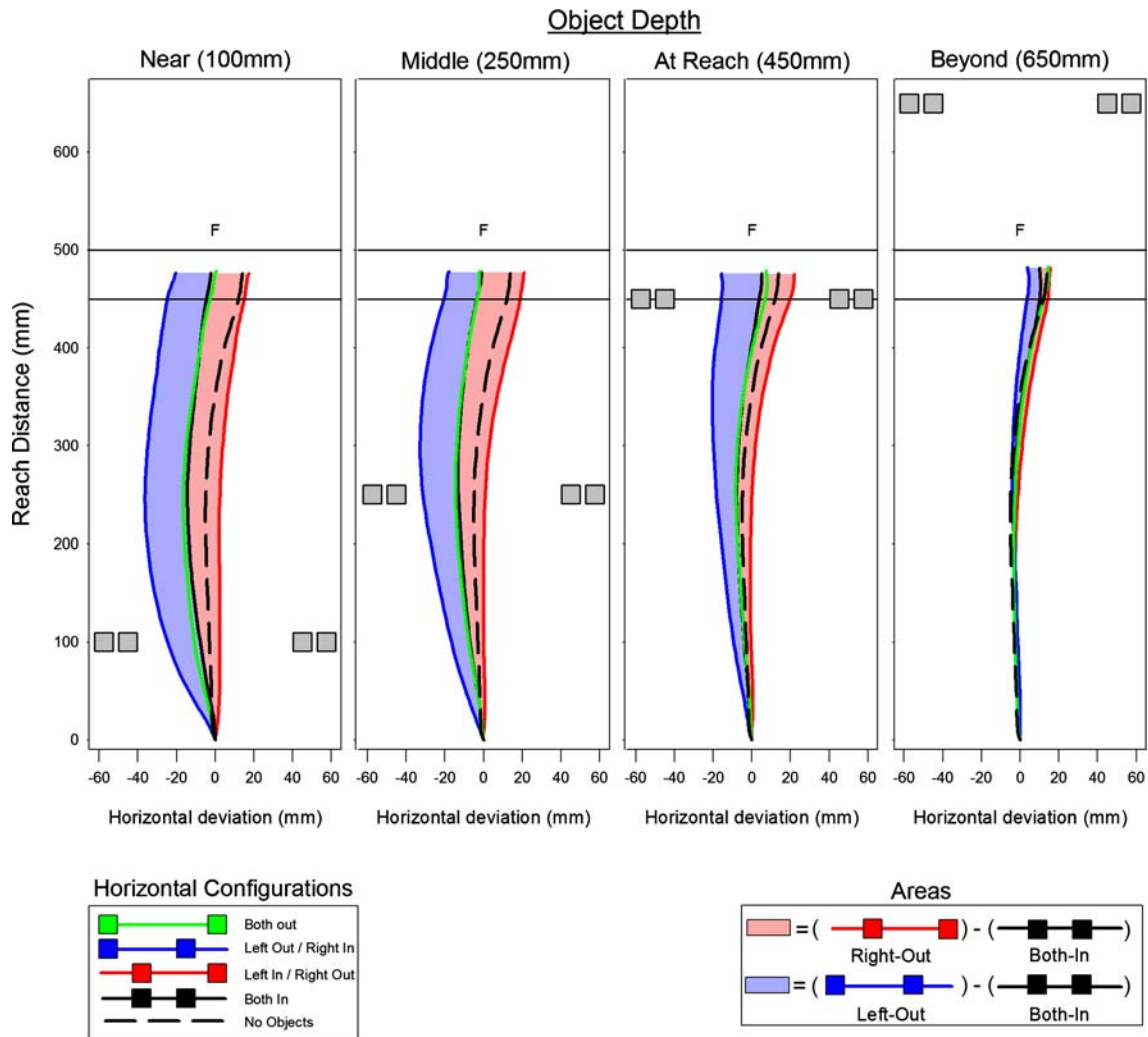
Mvmt Time (ms)	Depth					Configuration				
	Near	Mid	At reach	Beyond	<i>F</i>	B-in	L-out	R-out	B-out	<i>F</i>
	683.75	642.72	627.99	617.63	**	662.48	648.92	632.04	628.64	**
	Near >> rest					B-in >> B-out, R-out; L-out > B-out				
Peak V (mm/s)	Interaction* configuration x depth									
	B-in	L-out	R-out	B-out	<i>F</i>					
Near	1,559.21	1,674.35	1,724.94	1,771.32	**					
Mid	1,707.95	1,797.63	1,809.01	1,869.06	**					
At reach	1,884.97	1,903.52	1,947.86	1,965.75	*					
Beyond	1,902.77	1,923.48	1,970.44	1,966.75	*					
						B-in << rest; B-out > L-out				
						B-out > L-out; B-out >> B-in; R-out > B-in				
						B-out > B-in				
						B-out > B-in				
Area (mm <sup>2</sup> )	[R-out - L-out] Depth									
	Near	Mid	At reach	Beyond	<i>F</i>					
	15,655.0	13,648.9	9,011.9	1,967.0	**					
						Near >> rest; mid >> at reach, beyond; at reach > beyond				
X@100 (mm)	Interaction** configuration x depth									
	B-in	L-out	R-out	B-out	<i>F</i>					
Near	-9.08	-26.00	1.93	-11.60	**					
Mid	-8.06	-18.48	-.33	-8.37	**					
At reach	-4.46	-10.53	-.68	-3.84	**					
Beyond	-2.44	-2.60	-2.58	-3.81	NS					
						L-out << rest; R-out >> rest				
						L-out << rest; R-out >> rest				
						L-out < B-out, B-in; L-out << R-out				
						-				
X@250 (mm)	Interaction** configuration x depth									
	B-in	L-out	R-out	B-out	<i>F</i>					
Near	-16.25	-39.73	.72	-19.08	**					
Mid	-13.53	-33.90	.43	-16.40	**					
At reach	-8.93	-21.26	-1.24	-8.89	**					
Beyond	-4.28	-6.09	-3.17	-4.35	NS					
						L-out << rest; R-out >> rest				
						L-out << rest; R-out > rest				
						L-out < rest; R-out > B-out				
						-				
X@450 (mm)	Interaction* configuration x depth									
	B-in	L-out	R-out	B-out	<i>F</i>					
Near	-1.81	-20.38	18.16	.71	**					
Mid	-.28	-17.80	21.42	-1.60	**					
At reach	5.08	-15.58	21.78	7.39	**					
Beyond	10.28	3.86	16.39	14.69	NS					
						L-out < rest				
						L-out < rest; R-out > rest				
						L-out < rest				
						-				
Z@100 (mm)	Depth					Configuration				
	Near	Mid	At reach	Beyond	<i>F</i>	B-in	L-out	R-out	B-out	<i>F</i>
	68.43	62.69	59.49	59.37	*	63.82	64.08	61.43	60.64	**
	Near > mid, at reach					No significant pairwise				
Z@250 (mm)	Depth									
	Near	Mid	At reach	Beyond	<i>F</i>					
	87.79	79.77	76.83	77.33	*					
						Near >> mid; near > at reach, beyond				
Z@450 (mm)	Depth									
	Near	Mid	At reach	Beyond	<i>F</i>					
	39.32	37.30	38.87	42.87	*					
						Beyond > mid, at reach				

The means of the dependent measures in experiment 1 with significant effects from a depth × configuration two-factor ANOVA. Significant effects are indicated in the row with the measure name. With a significant single factor, the 'F' column shows an *F* test of main effects whereas with a significant interaction, it shows an *F* test of simple main effects (configurations @ depth). Results from pairwise contrasts are shown next to each significant *F* test, or below the compared means. \* & < or > =  $P < 0.05$ , \*\* & << or >> =  $P < 0.005$

### Area effects

The overall spatial effects of both depth and configuration on lateral deviation can be seen in Fig. 2, which plots the average reach trajectory (in the *x/y* plane) made for each configuration broken down across the four object depths. In addition to the trajectories, shown in Fig. 2 is the area between the right-out and both-in curves (filled in light red)

and the area between the left-out and both-in curves (filled in light blue). Reaches made in the presence of asymmetric configurations of objects caused the expected deviation away from midline, provided the objects were presented between the start and end point of the reach. Reaches made in the presence of symmetric configurations of objects were nearly identical. This was confirmed statistically by analyzing the total area difference between asymmetric curves



**Fig. 2** Overhead view (*x, y*) of average reach trajectories made for each depth and configuration in experiment 1, with areas filled for deviations due to asymmetric configurations. Each separate plot shows trajectories for each configuration at a different depth. *Gray squares* possible object depths, ‘*F*’ = fixation location, *horizontal lines* start and

end of target strip. Configuration trajectories: both-in (*black*), left-out (*blue*), right-out (*red*), both-out (*green*), no obstacles (*dashed black*). Areas: difference between both-in and right-out (*light red*), difference between both-in and left-out (*light blue*)

(right-out – left-out, red area + blue area in Fig. 2). As is clear from Fig. 2 and the reported means (see Table 1), the amount of deviation due to an asymmetric object configurations decreased as a function of object depth.

*Position effects*

For the three lateral measures (X@100, X@250, X@450) there was a significant depth × configuration interaction (see Table 1). Confirming the area results, the left-out and right-out curves were significantly to the left and right (respectively) of the symmetrical curves for the majority of the reach movement, provided that the objects were presented between the start and end points of the reach. Late in the reach, or when objects were presented at the at

reach depth, the right-out curve began to resemble the symmetrical curves, providing further evidence for the dominant role the right object plays in driving the observed avoidance behavior for right-hand reaches.

As an additional statistical test of these findings, treatment contrast follow-ups were conducted for the significant interactions seen for each of the lateral deviation measures. Thus, the difference [right-out – left-out] was examined at each object depth using a single-factor repeated-measures ANOVA, again with pairwise contrast follow-ups (see Fig. 3). For X@100, there was a main effect of depth,  $F(1.901, 22.818) = 54.087, P < 0.001$ , where objects closer in depth caused more deviation (all pairwise comparisons,  $P < 0.01$ ). The same pattern was observed for X@250: main effect,  $F(1.533, 18.392) = 42.647, P < 0.001$ ; (all pair-

wise comparisons,  $P < 0.05$ ). Finally, X@450 showed a significant main effect of depth,  $F(1.657, 19.885) = 6.803$ ,  $P < 0.01$ ; however, none of the pairwise comparisons reached significance. Critically, for X@450, the effect was driven by a similarity in the amount of deviation for all object depths except beyond. These analyses demonstrate that participants were reacting earlier to those objects that appeared closer in depth, but that the lateral deviation across depths becomes equivalent by the end of the reach.

The vertical deviation measures (Z@100, Z@250, Z@450, Table 1) showed higher early reach trajectories where there was more of an obstructing effect, that is, with objects close in depth and on the right side. Finally, at the end of the reach there was evidence that objects placed beyond the reach target led to reaches that landed further in depth, resulting in higher trajectories near the reach end point.

## Discussion

In this experiment, we examined the effects of objects that were potential obstacles to a reaching movement and how their effect on the trajectory of the movement varied as a function of their position. An analysis of temporal parameters revealed that objects close to participants in depth and close to the midline on the right-hand side caused more obstructing effects, manifested by longer movement durations and lower peak velocities. This is consistent with previous work on obstacle avoidance (Mon-Williams et al. 2001; Tresilian 1998, 1999).

We replicated previous studies with patients and controls (Milner and McIntosh 2004; Rice et al. 2006; Schindler et al. 2004) demonstrating that neurologically intact participants deviated their reach in response to asymmetrically

configured obstacles, provided those obstacles were positioned between where they started and ended their reach (see Fig. 2). Using the area between trajectories as a measure, we demonstrated that this deviation decreased as objects were moved further away in depth, and nearly disappeared when objects were placed past the reach target. In a further set of analyses, we demonstrated that the area effect was driven by a larger initial deviation to objects that were placed closer to the participant, and did not represent an overall difference in reach endpoint based on object depth (see Fig. 3).

## Experiment 2

Except for the changes described below, experiment 2 was identical to experiment 1.

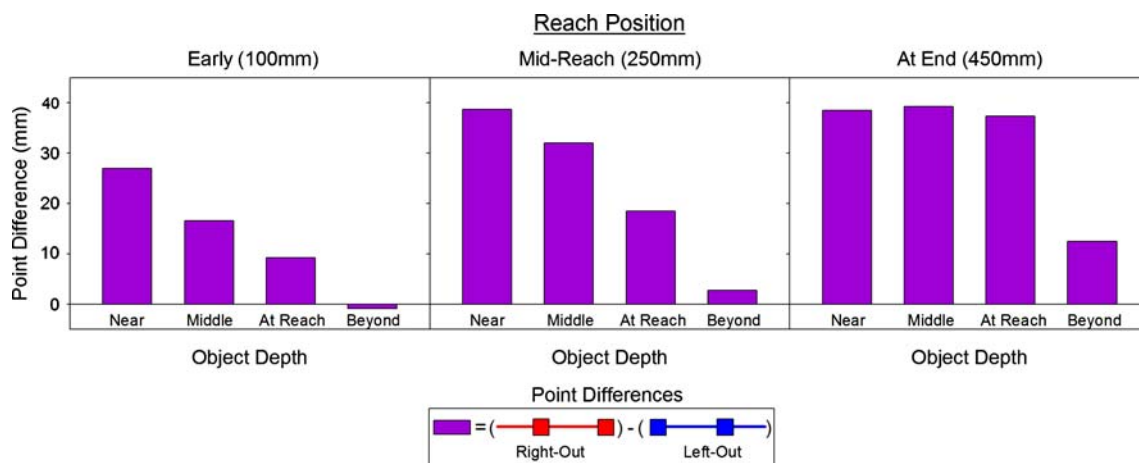
## Materials and methods

### Participants

A group of 20 right-handed (determined by self-report) adults (9 males) were included in this study.

### Materials and design

The near depth and both-out configurations were eliminated in the second experiment. Objects could be presented in four different size-pairs, both-tall, left-short/right-tall (referred to as left-short), left-tall/right-short (referred to as right-short), or both-short. Short objects were identical to tall objects except in height, where short objects were 2 cm high as compared to the 25 cm tall objects.



**Fig. 3** Horizontal deviation differences between the right-out and left-out trajectories for experiment 1. Point differences are shown in separate graphs for early (@100 mm in depth), mid (@250 mm) and end (@450 mm) reach positions. Each bar within a graph is the point

difference between trajectories made with objects at each depth. Obstacles placed closer to the participant caused earlier deviation, while all obstacle depths except beyond showed similar end points



## Procedure

The three depths, three horizontal configurations and four size-pairs were fully crossed and each repeated four times for a total of 144 trials. Trials were blocked according to the size-pair as follows (number of trials in brackets): both-tall (36), one-tall/one-short (72), and both-short (36). The left and right-short trials were collapsed into one block and were pseudo-randomly ordered. Also, the depth and configuration were pseudo-randomly ordered within each size block. An additional four trials with no objects were presented once at the beginning of the experiment, and once at the end of the experiment, so the entire experiment consisted of 152 trials.

Participants were randomly assigned to one of two different groups (ten participants in each group) which differed in the order that they received the size-pair blocks. The first group received: both-tall, one-tall/one-short, both-short. The second group received: both-short, one-tall/one-short, both-short.

In the second experiment, participants were not given any instruction about passing their hand between the two objects. If on trials with at least one tall object, participants ever went to the outside of the tall object instead of to the inside, they were told to try and stay between the two objects. Only three subjects ever used this strategy and no subject needed this instruction more than once.

## Data processing

Data processing was identical to the first experiment except for the additional removal of trials where subjects passed their hand to the outside of a tall object. In the second experiment <1% of trials were removed.

In the second experiment, linear interpolations that were required to deal with missing index and pinky IREDs occurred on <2% of trials. Interpolations, where required, were carried out across an average of less than five time points.

## Dependent measures and analysis

All measures were the same as experiment 1 except for the area measure. In experiment 2, the deviation caused by the left-out configuration (left area: both-in–left-out) was analyzed separately from the deviation caused by the right-out configuration (right area: right-out–both-in).

To analyze the effects of depth, configuration, and size, each of the dependent measures (except for the area between curves measure and on trials with no objects; see “Results” for note on the latter) was entered into a three-factor depth  $\times$  configuration  $\times$  size ( $3 \times 3 \times 4$ ) repeated-measures ANOVA. The only significant three-way interac-

tions were those involving the lateral deviation measures; for each of these measures, therefore, we carried out a two-factor (size and configuration effects at each depth) repeated-measures ANOVA (see Table 3). If there was a significant two-way interaction involving size, we went on to examine the size effects across the other factor (using single-factor repeated-measures ANOVAs). If there were any two-way interactions between depth and configuration, we examined the configuration effects across depth (using single-factor repeated-measures ANOVAs). For the area between curves measures, a two-factor depth  $\times$  size repeated-measures ANOVA was conducted. For the sake of consistency, simple main effects follow-ups were conducted on the left area even though the size  $\times$  depth interaction failed to reach significance ( $P = 0.15$ ). Post hoc follow-ups to significant main effects and simple main effects compared all possible pairwise comparisons of the relevant factor. Where there were significant effects (interaction effects or main effects) for dependent measures, the results are listed in Tables 2 and 3.

## Results

### *Trials with no objects and group differences*

A separate analysis was conducted to compare trials with objects present to trials with no objects present. For object trials we used two groups, an average of reaches made with two tall objects at the middle depth and an average of reaches made with two short objects at middle depth. We also split the trials with no objects into those that occurred at the beginning of the experiment and those that occurred at the end. We compared these four groups using a single-factor repeated-measures ANOVA. In general, tall objects obstructed movements more (longer movements and lower peak velocities) than small objects, which appeared to be treated more like the no object trials. Reaches made in the presence of objects were shifted to the left of reaches made during the first trials with no objects. However, the reaches made during the last no object trials were significantly faster and further to the left of the reaches made during the first no object trials, indicating a practice effect across the experiment. For full statistical analysis, and graphical representation of these results, see supplementary Table 2 and Supplementary Fig. 1.

Any differences between the two groups who received the different size-pair orders can be attributed to the practice effect described above. This interpretation is supported by the fact that there were no significant group differences during the mixed size trials, which were all presented during the middle of the experiment. For all analyses discussed in experiment 2, results are thus collapsed across group.

**Table 2** Dependent measures with significant one or two-way effects in experiment 2

Mvmt Time (ms)	Interaction** size x configuration					Depth				
	B-tall	L-short	R-short	B-short	F	Mid	At reach	Beyond	F	
B-in	533.58	526.87	521.84	498.76	*	520.23	516.20	508.42	**	
L-out	524.28	528.75	516.70	494.71	*	Mid >> beyond; at reach > beyond				
R-out	518.32	514.25	507.23	494.08	NS					
	For B-in and L-out: LS >> BS									
Rxn Time (ms)	Configuration									
	B-in	L-out	R-out	F						
	264.28	265.28	270.29	*	No significant pairwise					
Peak V (mm/s)	Interaction** size x depth					Configuration				
	B-tall	L-short	R-short	B-short	F	B-in	L-out	R-out	F	
Mid	1,941.7	2,052.0	2,129.1	2,164.7	**	2,113.956	2,128.856	2,156.434	*	
At reach	2,068.3	2,130.4	2,158.0	2,136.3	NS	B-in < R-out				
Beyond	2,163.4	2,219.8	2,223.2	2,210.1	NS					
	For Mid: BT < RS; LS < RS									
Time to PV (ms)	Depth									
	Mid	At reach	Beyond	F						
	225.04	221.00	220.11	*	Mid > at reach, beyond					
%Time to PV	Depth									
	Mid	At reach	Beyond	F						
	42.4	43.3	43.9	**	Mid >> beyond; at reach > beyond					
Area (mm <sup>2</sup> )	[Both-in – Left-out] *Size **Depth					[Right-out – Both-in] **Interaction size x depth				
	B-tall	L-short	R-short	B-short	F	B-tall	L-short	R-short	B-short	F
Mid	5,687.1	2,021.5	5,075.1	2,573.9	**	6,322.0	8,365.3	2,715.0	2,590.4	**
At reach	3,260.7	1,804.1	1,944.3	626.7	NS	5,243.8	3,831.2	4,277.5	5,831.4	NS
Beyond	-61.2	270.0	-1074.4	-349.4	NS	1,245.1	-45.5	2,715.0	1,660.0	NS
	For Mid: LS << BT; LS < RS					For Mid: BT > RS; BT > BS; LS > RS; LS > BS				
Z@100 (mm)	Interaction* size x depth					Interaction* configuration x depth				
	B-tall	L-short	R-short	B-short	F	B-in	L-out	R-out	F	
Mid	38.39	43.53	44.39	41.60	NS	43.06	43.13	39.74	*	
At reach	33.18	36.12	35.11	36.11	NS	34.78	35.57	35.03	NS	
Beyond	32.37	34.54	33.82	36.03	NS	34.10	33.90	34.56	NS	
	No significant pairwise					For Mid: B-in, L-out > R-out				
Z@250 (mm)	Interaction** size x depth					Interaction** configuration x depth				
	B-tall	L-short	R-short	B-short	F	B-in	L-out	R-out	F	
Mid	59.19	66.90	68.02	61.19	*	65.61	65.22	60.65	**	
At reach	50.15	51.39	51.21	51.36	NS	49.92	51.56	51.60	NS	
Beyond	48.39	48.94	48.89	50.86	NS	48.82	49.22	49.76	NS	
	No significant pairwise					For Mid: B-in > R-out; L-out >> R-out				
Z@450 (mm)	Depth									
	Mid	At reach	Beyond	F						
	31.11	26.23	28.43	*	Mid > at reach					

The means of the dependent measures (excluding horizontal deviation) in experiment 2 with significant effects from a depth × configuration × size three-factor ANOVA. None of these measures had significant three-way interactions. Significant effects are indicated in the row with the measure name. *F* tests results are shown comparing means in each row across the column levels. Results from pairwise contrasts are shown next to each significant *F* test, or below the compared means. \* & < or > =  $P < 0.05$ , \*\* & << or >> =  $P < 0.005$

### Temporal effects

As is shown in Table 2, the temporal components of reaches made in the presence of objects revealed a pattern similar to the results of the first experiment. Participants were slower (longer movements and lower peak velocities) when tall objects were closer to them in depth and on the right side.

Short objects, especially when located on the right-hand side of the work space, had less of an effect on reach trajectories. The time to peak velocity was longer for objects presented at the middle depth, and it also took longer in terms of the percent time to peak velocity. The reaction time effect seems anomalous and there is no specific explanation for why the right-out configuration slowed reaction time.

**Table 3** Dependent measures with significant three-way effects in experiment 2

Middle Interaction** configuration × size															
	B-in					L-out					R-out				
	B-tall	L-short	R-short	B-short	F	B-tall	L-short	R-short	B-short	F	B-tall	L-short	R-short	B-short	F
X@100	-14.41	-31.89	-1.69	-10.84	**	-22.16	-33.49	-10.12	-12.98	**	-5.80	-19.42	1.60	-8.79	**
X@250	-21.99	-48.09	0.644	-14.21	**	-36.84	-53.20	-13.84	-21.00	**	-5.57	-26.42	7.37	-7.96	**
X@450	6.17	-3.45	27.55	22.29	**	-6.02	-10.73	19.34	14.24	**	26.27	19.35	38.88	32.44	**
	For X@100: LS << rest; RS >> rest					For X@100: LS << rest; RS >> BT; BT < BS					For X@100: LS << rest; RS >> rest				
	For X@250: LS << rest; RS >> rest					For X@250: LS << rest; RS >> BT; BT < BS					For X@250: LS << rest; RS >> rest				
	For X@450: LS << RS; LS < BS; RS > BT					For X@450: LS << RS; LS < BS; RS >> BT					For X@450: LS << RS				
At reach															
	Size					Configuration									
	B-tall	L-short	R-short	B-short	F	B-in	L-out	R-out	F						
X@100	-8.12	-14.80	-7.37	-9.69	**	-10.94	-13.00	-6.05	**						
X@250	-12.05	-22.94	-8.78	-13.57	**	-16.46	-21.34	-5.21	**						
X@450	16.02	8.21	20.13	14.61	*	10.03	3.67	30.53	**						
	For X@100: LS << BT; LS << RS; LS < BS					For X@100: BI > LO; BI << RO; LO << RO									
	For X@250: LS << BT; LS << RS; LS < BS					For X@250: BI >> LO; BI << RO; LO << RO									
	For X@450: LS < RS					For X@450: BI > LO; BI << RO; LO << RO									
Beyond															
	Size					Configuration									
	B-tall	L-short	R-short	B-short	F	B-in	L-out	R-out	F						
X@100	-1.808	-3.967	-5.199	-5.707	NS	-4.652	-4.368	-3.491	NS						
X@250	3.331	0.028	-2.508	-3.081	NS	-1.623	-0.926	0.875	NS						
X@450	47.763	45.116	43.670	37.126	NS	41.062	43.286	45.907	NS						

The means (all in mm) of the horizontal deviation measures for experiment 2 grouped by depth. All measures (X@100, X@250, X@450) had a significant three-way interaction between depth, configuration and size in a three-factor ANOVA (all  $P < 0.05$ ). Shown are the results for a size × configuration two-factor ANOVA at each depth. Only at the middle depth was there a significant interaction. For the at reach depth, only main effects were present, and for the beyond depth, no effects were present.  $F$  tests compare size @ configuration for the middle depth, and size and configuration independently for the at reach and beyond depths. Results from pairwise contrasts are shown below the means for each significant  $F$  test. \* & < or > =  $P < 0.05$ , \*\* & << or >> =  $P < 0.005$

*Area effects*

Plotted in Fig. 4 is each of the reach trajectories (with area shaded as in experiment 1) for the 36 different depth × size × configuration conditions. As shown in Table 2, both the left and right areas reflect the fact that the deviation of the reach is affected by the size of the objects only at the middle depth. At this depth, tall objects, especially when placed on the right-hand side, caused significantly more deviation than short objects. The effect of depth on deviation observed in the first experiment was replicated here with objects closer in depth causing more deviation.

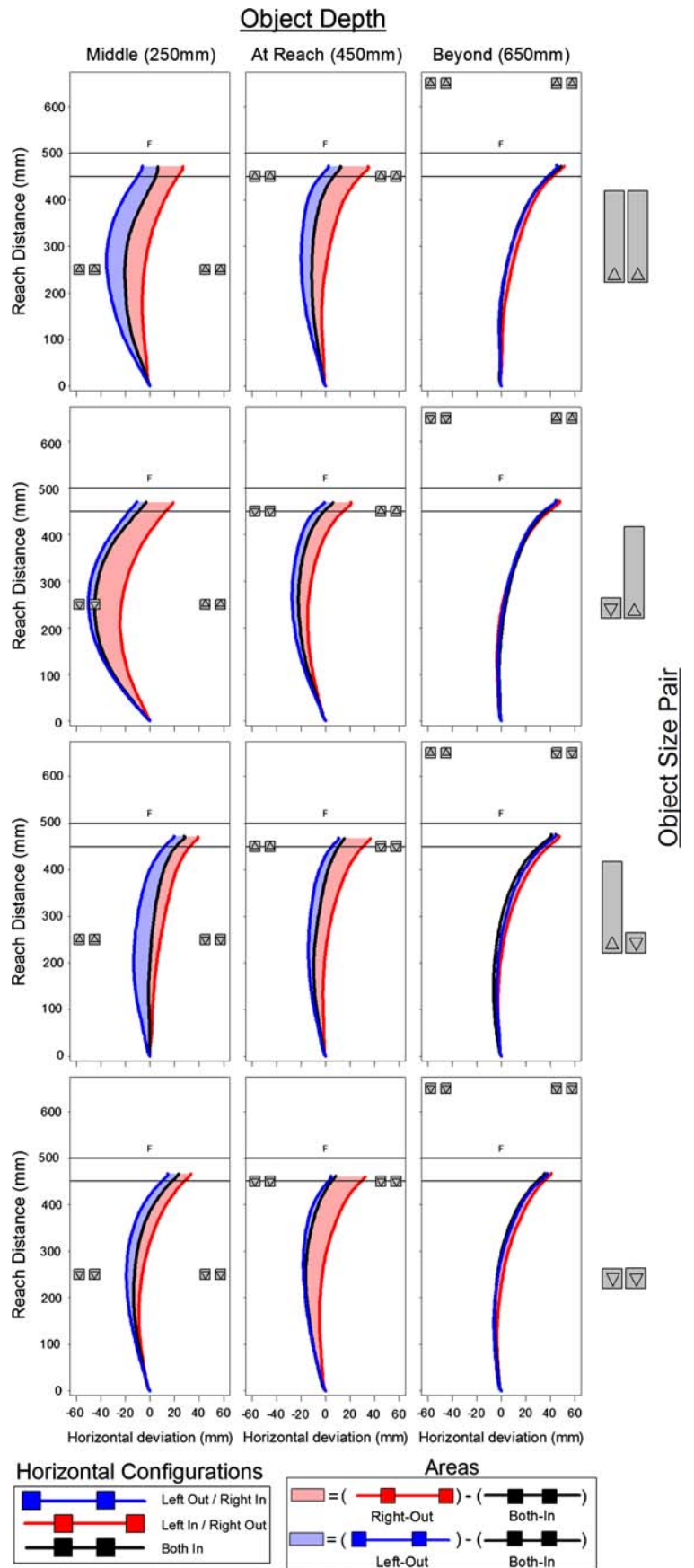
*Position effects*

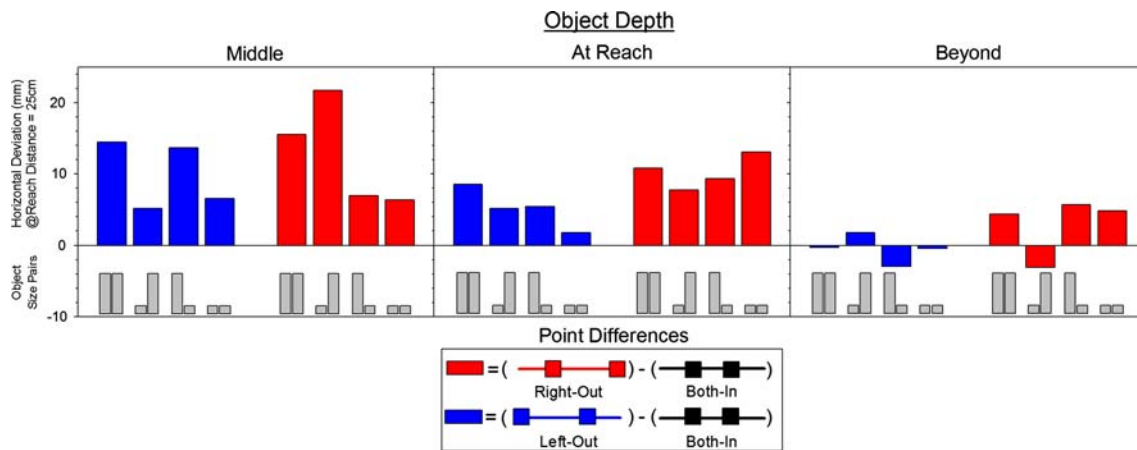
Since the vertical deviation measures (Z@100, Z@250, Z@450) did not show any three-way interaction (and are thus shown in Table 2) they will be discussed first. Objects presented at the middle depth tended to cause higher trajectories for pairs of objects that differed in size. In addition, configurations bringing objects close to midline on the right

(again only at the middle depth) caused higher trajectories. While an interaction was not significant, this suggests that small objects close on the right-hand side, especially when paired with tall objects, are avoided by moving the hand vertically.

The lateral deviation measures (X@100, X@250, X@450) were the only ones to show a significant three-way interaction, and thus appear in their own table (Table 3). There is a replication of the depth effect from experiment 1, where objects placed beyond the reach target had no significant effect on lateral deviation, regardless of size or configuration. For the at reach depth, there were significant, but independent, effects of size and configuration. In the size effect, reach trajectories deviated to the left of a tall object on the right, but only when it was paired with a short object. For configuration, the left-out curve was to the left, and the right-out to the right, of the both-in curve. Importantly, for the at reach depth, these patterns of deviation were independent of object size, suggesting that short and tall objects were treated similarly. At the middle depth, however, a significant interaction between size and configuration was

**Fig. 4** Overhead view ( $x, y$ ) of average reach trajectories made for each depth, configuration and size combination in experiment 2, with areas filled for deviations due to asymmetric configurations. Each separate plot shows trajectories for each configuration at a different depth and size. *Gray squares* possible object depths with *up-triangle* indicating tall object, *down triangle* indicating short object, 'F' = fixation location, *horizontal lines* start and end of target strip. Configuration trajectories: both-in (*black*), left-out (*blue*), right-out (*red*). Areas: difference between both-in and right-out (*light red*), difference between both-in and left-out (*light blue*)





**Fig. 5** Mid-reach (250 mm) horizontal deviation differences between the right-out and both-in (red bars) and left-out and both-in (blue bars) trajectories for experiment 2. Point differences between trajectories made with objects at each depth are shown in separate graphs. Each bar within a graph is the point difference between trajectories made with

objects of each size-pair. We see all the major results from experiment 2 represented in this graph: No effect of objects beyond the reach target; an effect of configuration (especially objects on the right) but not of size at the at reach depth; an effect of configuration and size at the middle depth with taller objects causing more deviation

observed. This interaction was driven by participants deviating away from tall objects when paired with small objects.

To clarify the above findings, the mid-reach lateral deviation differences for the left-shift [left-out – both-in] and right-shift [right-out – both-in] were examined and are plotted in Fig. 5. This figure provides a good summary of the effects we observed in the second experiment. Specifically, lateral deviations were not affected by objects placed beyond the reach target, and critically, objects of different sizes had similar effects at the at reach depth, and different effects at the middle depth. For objects at the middle depth, tall objects caused more deviation than short objects. In order to assess these differences statistically, a two-factor repeated-measures ANOVA (depth  $\times$  size) for both the left-shift (blue bars, Fig. 5) and right-shift (red bars, Fig. 5) point differences was conducted. For both, there was a significant depth  $\times$  size interaction [left-shift:  $F(4.43, 79.80) = 2.446$ ,  $P < 0.05$ ; right-shift:  $F(3.52, 63.32) = 5.59$ ,  $P < 0.001$ ]. Simple main effects revealed that both the left and right-shift differences had significant effects of size *only* at the middle depth (left-shift:  $F(2.64, 50.06) = 6.91$ ,  $P < 0.001$ ; right-shift:  $F(1.917, 36.430) = 11.371$ ,  $P < 0.001$ ). Pairwise comparisons of size at the middle depth show that for the left-shift, this result was driven by a difference between the trials with a tall object on the left (both-tall and left-tall) and the trials with a short object on the left (both-short and right-tall; both-tall  $> *$  right-tall; left-tall  $> *$  right-tall,  $*P < 0.01$ ). Conversely, for the right-shift, the result was driven by a difference between trials with a tall object on the right (both-tall and right-tall) and trials with a short object on the right (both-short and left-tall; both-tall  $> **$  left-tall; both-tall  $> *$  both-short; right-tall  $> **$  left-tall; right-tall  $> *$  both-short  $**P < 0.005$ ,  $*P < 0.05$ ). Taken

together, these results provide strong evidence for an obstacle avoidance system that is sensitive to the size and position of potential obstacles and incorporates these features into reach trajectories automatically.

## Discussion

In line with the results from the first experiment, objects that offered genuine constraints to reaching movements caused those reaches to slow down, lengthening movement time and lowering peak velocity. This meant that tall objects presented at the middle depth and on the right-hand side showed the largest effects. Short objects in the same position had smaller effects on reaching and resulted in trajectories that were more elevated. Additionally, the expected lateral deviation due to asymmetrically aligned objects was observed, provided the objects were presented between the participant and their reach target. We also observed a significant practice effect, indicated by a dramatic shift in the position of reaches made with no objects present at the beginning as compared to at the end of the experiment.

With respect to the effects of object size on trajectories, several analyses indicated that only at the middle depth were tall objects and short objects treated differently. Both the analyses of area and lateral deviations at a specific point showed that, at the middle depth, tall objects caused more deviation than short objects. These analyses also demonstrated that at the at reach depth, it was the right object (regardless of size) that caused more deviation, further supporting the hypothesis that a right-hand reach will be more affected by obstacles on the right side of space, especially toward the end of the reach.



## General discussion

Taken together the results of this study confirm previous findings with patients and controls (Milner and McIntosh 2004; Rice et al. 2006; Schindler et al. 2004) that an intact obstacle avoidance system (likely requiring the dorsal stream) is sensitive to the horizontal arrangement of two non-target objects placed mid-reach, and extend the findings to include a sensitivity to the depth and size of the two objects. The current study also extends previous work on obstacle avoidance behavior during reach-to-grasp movements (Mon-Williams et al. 2001; Tresilian 1998, 1999), demonstrating that participants performing a simpler reach-to-point task show a sensitivity to obstacle positions throughout the workspace and in a number of possible configurations. In general, objects that were placed between the start and end points of the reach resulted in trajectories that avoided them and were slower. Objects that were closer to a participant's reaching (right) arm and closer in depth resulted in even larger deviations and slower reaches, indicating that obstacle avoidance scaled with the amount a given object configuration constrained the reach. In contrast, across both temporal and spatial measures, non-target objects that were placed past a reach target played a significantly reduced role as obstacles. Object-size sensitivity was most clearly demonstrated by the fact that different sizes of objects only had an effect at the middle depth, where tall objects caused more deviation and slower reaches, but not at the at reach depth, where both short and tall objects had similar obstructing effects. This effect of obstacle size stands in contrast to the null effect of obstacle size reported previously (Mon-Williams et al. 2001) and demonstrates that the obstacle avoidance system is sensitive to the size of an object given an appropriate configuration. In the Mon-Williams et al. study (2001), it is likely that no effects of object size were observed since objects were always positioned close to the reach target (similar to the at reach depth in the current study). Thus, the results of both the previous and current study are easy to interpret: at the point where a reach (or grasp) is terminated, short objects offer just as much of an impediment as tall objects. The current study also demonstrates that the obstacle avoidance system is conservative when evaluating potential objects in that two small objects at the middle depth, while causing smaller changes in the reach trajectories than tall objects, still resulted in avoidance behavior. Thus, we conclude that the obstacle avoidance system is a sophisticated, fast acting system that is sensitive to object size and depth and conservative when evaluating potential obstacles.

While the current experiment was designed to extend our knowledge of the obstacle avoidance system, there are other explanations of non-target object effects that warrant discussion. In studies where non-target objects function as

distractors, observed deviations are thought to be the result of an imperfect inhibition of automatically generated motor plans directed toward the non-targets (e.g. Howard and Tipper 1997; Tipper et al. 1997). Other studies have suggested that non-target object are treated as landmarks such that visually salient objects 'attract' reach trajectories toward them (e.g. Diedrichsen et al. 2004). The performance of participants in the current study on trials in which the non-target objects were placed beyond the reach target (or on trials in which objects of different sizes were placed at the midline) strongly suggests that landmark and distractor effects were not at play. For objects (especially tall objects that were easily seen) placed past the reach target, both the distractor and landmark hypotheses would predict that these salient objects should cause deviation toward the object nearest to the reach endpoint. As was demonstrated in both the first and second experiment, however, objects placed past the reach target did not significantly affect deviation (see Figs. 2, 4). Trials with different sizes of objects at the middle depth also suggest that the non-target objects in the current study were being treated neither as distractors nor as landmarks. Since the smaller object is clearly visible, it should still function as a distractor or a landmark. As observed in experiment 2, however, and shown in the left column of graphs in Fig. 4, tall objects caused significantly more deviation than short objects at the middle depth. Thus, as predicted, the results of the current study are best explained as obstacle avoidance since deviations of the reaching movements were in almost exact accordance with the degree to which the two non-target objects obstructed the reach.

As has been discussed, this study was motivated by, and adapted from, previous work with patients that indicated an intact dorsal stream was necessary for obstacle avoidance (McIntosh et al. 2004a, b; Milner and McIntosh 2004; Rice et al. 2006; Schindler et al. 2004). While the current study does not directly test the neural locus of this ability, the automaticity observed in reach movements does support the dorsal-stream hypothesis. The reaction time data, in conjunction with the fact that these reaches were performed without visual feedback, suggest a system with limited conscious control. Specifically, reaction times were generally fast and were not significantly affected by the size, depth and configuration manipulations. In order to provide further insight into the underlying neural architecture of obstacle avoidance, however, we are currently designing obstacle paradigms for use in an fMRI environment. Despite its likely control by the dorsal stream, we believe obstacle avoidance presents an interesting case where traditionally ventral-stream object properties are likely to affect behavior. For example, one would expect participants to be sensitive to the harmful nature of an object (like a cactus) and give these objects a wider berth when making reaches.

However, the danger an object presents is not a property that the dorsal stream, specialized for visuo-motor transformations, is thought to process. Thus, as obstacle avoidance is a behavior that provides a window into the convergence of the dorsal and ventral streams, studying it with functional brain imaging is an important future pursuit.

In addition to unanswered questions regarding the neural underpinnings of obstacle avoidance, it remains an open question as to what properties of non-target objects, aside from position and size, are relevant to its avoidance. Similarly, while the current study demonstrated that non-target objects presented during movement planning affected trajectories, it is unknown if this information is available for online corrections made during the reach. Finally, even though the distractor and landmark hypotheses appeared to play no significant part in determining the reach behavior observed in this study, more work needs to be done to fully clarify the differing roles that distractors, reference frames and avoidance have on reach movements. One specific question is to look at avoidance behavior in cases where the to-be-avoided objects are, on some trials, actually the target of the action, thus increasing their likelihood of functioning as distractors. As has been shown previously, non-target object features which overlap in meaningful ways with the target can have a significant impact on goal directed actions in ways that are irrelevant to avoidance (i.e. changes in grip aperture caused by differing sizes of fruit, Castiello 1996). These, and other genuine distractor effects, as well as those reported for landmarks (Bridgeman et al. 1997; Diedrichsen et al. 2004; Obhi and Goodale 2005), need to be separated from the avoidance behavior shown here. Thus, the current study provides an important step in understanding the seemingly simple yet empirically complicated task of obstacle avoidance.

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