On the relation between nontarget object location and avoidance responses

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The presence of nontarget objects influences kinematic parameters of reaches toward target objects. In previous studies, several different nontarget positions have been used. Taken together, these studies suggest that when the horizontal or vertical distance to nontargets is decreased, avoidance responses are more pronounced. Furthermore, responses to nontarget objects are asymmetrical across workspace, i.e., responses in the presence of equidistant nontargets on the inside and the outside of the reaching arm are different. However, these studies have provided a coarse overall picture of the effect of nontarget location. Therefore, the aim of this experiment was to systematically map the avoidance responses across the workspace in order to determine in detail the relation between nontarget position and the avoidance response. Specifically, we were interested in the contribution of four parameters to the reaching response: the nontarget's horizontal and vertical position, its distance from the starting position, and its angle with the vertical midline of the workspace. Participants were asked to perform reaches towards physical targets while nontargets were present in 1 of 24 different positions. Our results replicate horizontal and vertical effects of the nontarget object on reaching behavior. We also replicate stronger avoidances of nontargets on the outside of the reaching limb compared to nontargets on the inside. Furthermore, our results provide a detailed overview of the interaction between these factors and demonstrate that there is a "hot" region qua nontarget positions that prompt the strongest responses. Lastly, our results provide evidence that support a fine-grained spatial resolution of nontarget motor representation.

Introduction

Obstacle avoidance is a skill that humans possess in a number of movement domains, which is important for successfully acting in and upon our environment. For hand movements, obstacle avoidance is the ability to steer the hand around objects that obstruct movement toward a target. Research has determined that people are generally well able to perform these movements under a myriad of conditions: whether the nontargets are close to the hand (e.g., Mon-Williams, Tresilian, Coppard, & Carson, 2001) or next to the target (Biegstraaten, Smeets, & Brenner, 2003), large or small (Chapman & Goodale, 2008), oriented vertically or diagonally (Kritikos, Bennett, Dunai, & Castiello, 2000), close or further away in distance (e.g., Chapman & Goodale, 2008; Rice et al., 2006), the avoidance response is ostensibly subtle and precise (Tresilian, 1998). This is reflected by the fact that the hand veers smoothly around or away from a (partially) obstructing object with a minimum distance between hand and object (Dean & Bruwer, 1994). Therefore, kinematic parameters of the movement appear to be altered to reduce the risk of collision (Hamilton & Wolpert, 2002). These parameters include the deviation of the movement (i.e., the change in trajectory of the hand relative to a move in a workspace without an obstacle present), but also movement speed, grip aperture, movement time, and reaction time. The same spatial and temporal adaptations are noticed when nontargets are not necessarily obstructing the movements of the limbs towards the target (e.g., Tipper, Howard, & Jackson, 1997; Welsh, 2011).

It has been suggested that avoidance responses are primarily dependent on dorsal stream information (Rice et al., 2006; Schindler et al., 2004; Striener, Chapman, & Goodale, 2009), especially the egocentric location of the obstruction (e.g., Chapman & Goodale, 2008). Indeed, it is known that horizontal and depth position affect hand movements and also that ipsilateral nontargets cause larger deviations than contralateral nontargets (Chapman & Goodale, 2008; Dean & Bruwer, 1994; Meegan & Tipper, 1998, 1999; Menger, Van der Stigchel, & Dijkerman, 2012; Mon-Williams et al., 2001; Pratt & Abrams, 1994; Tipper, Lortie, & Baylis, 1992). However, several questions remain as to the nature of those effects: (a) What is the precise relation between horizontal-vertical position of the nontarget and the avoidance responses, i.e., is there a linear decrease or an abrupt shift in avoidance responses with increasing horizontal and vertical distances? (b) How do the horizontal and vertical positions of nontargets interact, i.e., is there a single hotspot or are there multiple hotspots at which avoidance responses are greatest? (c) Can different spatial locations of nontargets be lumped together or is the avoidance system as subtle and precise as suggested by Tresilian (1998) in that it generates a unique response to each layout of the workspace, i.e., is the spatial resolution of nontarget position coarsely or finely grained during visuomotor control?

Therefore, we believe it is worthwhile to systematically manipulate the location of the nontarget across 24 positions to map out the location effect in detail. Because hand trajectories are our behavioral measure of interference during visuomotor planning by nontarget objects, this setup allows us to investigate the spatial resolution of the nontarget motor representation. By placing the nontarget at many different locations we can determine whether the spatial resolution of the location representation is coarse or fine: Either there are differentiated responses to nontargets at different locations when the objects are close to each other (fine) or not (coarse). In addition, by using many different locations we can disentangle the unique contributions of the horizontal and vertical position of the nontarget, as well as the angle toward the nontarget (with respect to straight ahead) and the distance to the target. Angle and distance are a way to define position in an egocentric reference frame and therefore more likely to drive behavior. Proper identification of the relevant parameters can then lead to a more quantified understanding of obstacle avoidance: Simply put, if distance is a predictor of avoidance response, then how much distance leads to how much avoidance response?

By using many different nontarget locations during this experiment we are also able to observe the transition of nontargets from obstructing to no longer obstructing movement toward the target. In the latter case, participants are possibly only distracted by the presence of nontargets. However, whether the behavioral response to nontarget objects are better qualified as distractor interference (Tipper et al., 1997) or obstacle avoidance (Tresilian, 1998) is a discussion beyond the scope of this paper. For now, we assume that both can account for deviations to reaching behavior when objects are present. In a recent model by Cisek and Kalaska (2010), biases during target selection (distractor interference) and the specification of the action so as to avoid collision (obstacle avoidance), are postulated to operate in parallel and involve similar neural processes. Therefore, as attentional allocation and movement planning are closely related (see also Deubel & Schneider, 2003; Rolfs, Lawrence, & Carrasco, 2013), reported effects might not be uniquely attributable to either attentional allocation or movement planning. Indeed, if the processes operate in tandem, it is difficult to see where one influence stops and the other begins. With the current experiment we aim to underline this parallel processing by demonstrating that there is a gradual shift in strength of behavioral responses to obstacles that offer different levels of obstruction. On the contrary, if we would find a sudden drop in avoidance responses with increasing nontarget distance, this would suggest that the behavioral response to nontarget is indeed driven by only, or much more strongly, the obstruction the nontargets offer in this experiment. Thus, if indeed nontargets are relevant during action specification as well as bias action selection—processes that run in the same neural substrate—we do not expect an abrupt shift in movement deviation as horizontal or vertical distance of the nontarget increased.

It is important to note that the behavioral response is not a simple response to only the nontarget location. Indeed, movement trajectories are the result of a complex interplay between different motor control processes. First, properly controlling an avoidance movement may require a certain in-between-posture of the acting limbs during movement to prevent a collision with the nontarget (Rosenbaum et al., 2009; Vaughan, Rosenbaum, & Meulenbroek, 2001). This will prompt a mean curved movement trajectory over trials that deviates from a mean control movement trajectory over trials. Additionally, the requirement to have little positional variance at the location of the nontarget, that is, to be accurate and thereby reduce the chance of collision, may be revealed by characteristics of trajectories over repetitions of trials. For instance, promoting limb stability near nontarget objects may lead to little variance in position in curved movement trajectories. In contrast, there is no need to be accurate when there is no constraint on accuracy as is the case when no or a far-away nontarget is present. In this light, we propose...
to look at the variance of behavioral measures in addition to the means extracted from hand trajectories as our behavioral measures of interference elicited by nontarget objects during visuomotor planning. This is based on the assumption that humans can minimize limb position variability (or increase accuracy) during movement.

We designed an experiment to systematically map the effect of nontargets on hand trajectories. Right-handed participants were asked to perform reach-to-grasp movements toward a physical object with a physical nontarget present in the workspace. The nontarget could be located at 24 positions that were ipsi- and contralateral to the reaching hand. In other words, the nontargets could be on the inside or outside of the hand when it moved to the target.

**Methods**

**Participants**

We determined the sample size using power analysis software, viz. G*Power (Franz Paul, Universität Kiel, Germany). We obtained a partial $\eta^2$ from an earlier study (Menger et al., 2012). The effect size, $f$, was then determined to be 0.29. This related to the difference in hand movements between the different obstacle location conditions (i.e., a main effect of nontarget location on the deviation of the hand). Menger et al. (2012) found an effect in two separate experiments each with a population of 10 participants. The effect size of 0.29 will be detected with a precision $\alpha = 0.05$ (two-sided). With $\beta = 0.05$ (power = 95%), and 24 conditions, 10 participants were included in total. Three men and seven women volunteered for this study in exchange for curricular credit and gave their informed consent. All participants were right handed and had normal or corrected-to-normal vision. The faculty’s institutional review board under the Medical Research Act issued a formal written waiver that this research project did not require approval from a Medical Ethics Review Committee.

**Apparatus and stimuli**

The participants were seated at a white table (610 mm × 1220 mm). The table had a surreptitious workspace of 400 mm × 400 mm in which the experimental task was performed. Two buttons were embedded along the midline of the workspace in the table: one start button, located in front of the participant and one target button that was at a distance of 400 mm from the start-button at a 0° angle. The target button responded to a target being lifted from it. Pine wooden cylinders (150 mm height × 50 mm diameter) were used as target object and as nontarget object.

Nontargets were placed at one of 24 possible locations in the workspace. The locations were defined by grid formed by four horizontal and six vertical dimensions. Figure 1 provides a top-down overview of the spatial locations of possible nontargets. The spatial locations were chosen so as to coincide with earlier work (Chapman & Goodale, 2008, 2010; McIntosh et al., 2010).
al., 2004; Meegan & Tipper, 1998; Menger et al., 2012; Rice et al., 2006; Tipper et al., 1997). Egocentric distance and angle from the starting button to the nontargets are given in Table 1, while Figure 1 also gives an example of the angle and distance of a single nontarget.

Participants wore PLATO LCD goggles (Translucent Technologies, Toronto, Canada), and MiniBird magnetic markers (Ascension Technology Corporation, Burlington, USA) that permitted, respectively, manipulation of visual feedback and kinematic tracking with a sampling rate of 100 Hz over 3 s. The tracking markers were placed at the tips of participants’ right index finger and thumb to measure their spatial positions with 0.1 mm accuracy. These locations have been reported earlier as sites for markers (see e.g., Mon-Williams & McIntosh, 2000) and are considered to be the focus of prehension research (Ansuini, Tognin, Turella, & Castiello, 2007). Care was taken to avoid situations in which the width of the marker itself interfered with the movement. By fixing the cables to the participants’ arms and the table with tape and elastic participants could move their hands and arms without restriction.

### Table 1. Horizontal and vertical positions of nontargets with associated distances from starting button (in mm) and angular difference (in degrees) with respect to straight ahead (0°).

<table>
<thead>
<tr>
<th>Nontarget’s vertical position</th>
<th>−100</th>
<th>−50</th>
<th>0</th>
<th>50</th>
<th>100</th>
<th>150</th>
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<tr>
<td></td>
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<td>−14°</td>
<td>0°</td>
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<td>0°</td>
<td>27°</td>
<td>45°</td>
<td>56°</td>
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</table>

Our aim was to create a pyramid, where responses between the outermost, innermost, and in-between conditions would be similar instead of inherently biased by the use of the right arm. There was one control condition and there were 24 experimental conditions that were defined by the XY coordinates of the nontargets center relative to the starting button [vertical position (100, 150, 200, 250 mm), horizontal position (−100, −50, 0, 50, 100, 150 mm)]. All conditions were presented seven times, which makes a grand total of $(24 + 1 \times 7) = 175$ trials excluding 25 practice trials. In addition, the experiment was divided into two blocks to allow for a post-hoc split-half comparison. All trials were presented in a random sequence.

### Procedure

Participants were instructed to execute their reach-to-grasp movements with their right hand. The participants were given the instruction to start the movement as fast as possible after hearing an auditory cue, and also to smoothly reach and grasp the target object without touching the possible nontarget. We further told participants to grasp the target with thumb and index finger halfway along its vertical axis. This particular constraint at the end of the movement combined with both the movement constraints offered by the nontarget and the selected starting posture was used to increase behavioral consistency. This way the most direct trajectory to the target never went over the top of the obstacle or passed the inside of the obstacle when it should have gone passed the outside or vice versa. Nonetheless, sometimes participants would not select a consistent route to the target across conditions by, e.g., going round the outside once and along the inside the other times. Because these switches did not occur frequently during a given experiment (i.e., more than once or twice) the aberrant trajectories were excluded from further analysis (i.e., treated as outliers).
Before each trial the experimenter soundlessly placed the target object and nontarget on the workspace. After trial setup the PLATO goggles would open, thereby granting vision of the workspace to the participant. After a short delay (800–1200 ms) an auditory signal cued the participants to perform the task as instructed: the participant had to reach towards, grasp, and lift the target object with their thumb and index finger. Once the target was lifted by the participant movement data collection ceased. Upon task completion the participant put down the target and used their index finger to press the start button. This closed the PLATO goggles and ended the trial. After pressing of the start button, participants were required to hold their index finger and thumb at that location while awaiting the start of the next trial.

Dependent measures and analysis

The raw trajectory data of each trial was filtered by using a dual low-pass second-order Butterworth filter with a cut-off frequency of 20 Hz (see also: Mon-Williams et al., 2001; Tresilian, Mon-Williams, Coppard, & Carson, 2005). The filtered trajectory data was then normalized using a cubic spline interpolation into 100 samples (see also: Smeets & Brenner, 1995; Tresilian et al., 2005).

Using the position data and stimulus presentation data the following measures were computed:\(^1\): reaction time (the time between the auditory cue and movement onset), movement time (the time from movement onset until the end of the reach-to-grasp movement), grip aperture (the three-dimensional distance between thumb and index finger markers), peak velocity (the maximum velocity attained during movement), time to peak velocity (the time from movement onset until peak velocity was reached), deviation at passing (distance between the location of the index finger and the edge of the nontarget at the moment the hand passed the vertical position of the middle of the nontarget), and error at passing (the standard error computed for deviation at passing across repetitions of a condition). For each dependent variable, we computed an individual difference score between the experimental and the control condition. To do this for the deviation at passing score, we specified the deviation in the control condition (in which no nontarget was present) relative to the location of the nontarget in the respective experimental condition.

In order to build heat maps of the workspace we further expressed the deviation for a given participant and location as a fraction of the sum of deviations at all locations and then averaged that over participants (henceforth: summed deviation fraction). This way the distribution of the deviations, which is not constant across participants (see also Figure 2), could be compared.

Trials were rejected if the reach was initiated before the starting cue was given, the reach did not end within the recording window (3 s), or because of unforeseen recording errors. No participants were rejected because less than 10% of their trials were excluded from further analysis.

Results

We performed an initial Repeated Measures Analysis of Variance (henceforth: RM ANOVA) with an extra factor block (two levels: first and second) and within subject factors horizontal position (six levels: @X-100, @X-50, @X0, @X50, @X100, @X150) and vertical position (four levels: @Y100, @Y150, @Y200, @Y250). Below, these locations may be referred to as “middle, medial, and lateral” and “close and far” (in depth), respectively. In addition, locations to the left of the middle were considered as on the inside of the reaching arm and locations to the right were considered as on the outside of the reaching arm. Our analysis showed no significant difference between reaches performed in the first half of the experiment versus the second half of the experiment for all dependent measures (all ps > 0.05). Therefore, split half data were collapsed. When descriptive statistics are reported ‘±,’ always refers to ±1 standard error of the mean.

Deviation at passing

A main effect was found for vertical nontarget location, \(F(3, 27) = 7.28, p < 0.01\), partial \(\eta^2 = 0.35\). The mean deviation at passing for the closest nontargets was 39.7 mm (± 8.7), for the intermediary vertical positions it was 33.5 (± 6.8) and 33.0 (± 7.6), while for the furthest vertical positions, i.e., the furthest in depth, it was 25.7 mm (± 7.1). This indicates that participants more strongly deviated away from nontargets closer in depth than from those further away. The effect of vertical position is further illustrated in Figure 2, which shows the heat map we calculated from deviation data of index finger trajectories. Specifically, positions closer in depth to the starting position are hotter than those further away.

Another main effect was determined for horizontal position, \(F(5, 45) = 18.9, p < 0.001\), partial \(\eta^2 = 0.87\). The mean deviation at passing for the middle nontargets was 57.0 mm (± 3.4), for the inside medial and outside medial nontargets it was 40.4 (± 2.3) and 53.4 (± 2.3), respectively. The inside lateral nontargets evoked a mean deviation at passing of 5.34 (± 1.85), and for the less lateral nontargets and the extreme lateral nontargets on the outside the deviation at passing was 33.2 (± 1.0), and 8.49 (± 1.3), respectively. This suggests that participants
Figure 2. Discrete heat maps showing averaged (big panel) and individual (small panels) avoidance responses to nontarget locations. Target and starting location are shown as a white-filled circle and gray-filled circle, respectively. Color denotes the magnitude of the
avoidance responses where hot colors (red, orange) are strong responses and cold colors (green, blue) are weak or no responses (blue). In this case avoidance responses are expressed as a fraction of the summed deviation for a given participant, which was then averaged. A strong response is therefore equal to one (dark red) and a weak response is close to zero (dark blue).

Figure 3. Mean deviation score for all conditions. Mean deviation scores sorted per vertical position category. Error bars represent standard error of the mean. Lines with asterisks denote significant differences between conditions on Bonferonni-corrected paired $t$ tests. Deviation at passing is relative to the control condition, so a score of zero represents the control condition is this figure. The dotted line represents the upper bound of the between subjects standard error of the control condition. White asterisks indicate $ps < 0.002$ for one-sample $t$ tests of experimental condition with the control condition referant (0).
additional comparison with the control condition in the same figure. Particularly, we further performed one-sample t tests to ascertain whether the experimental conditions differed from the control condition. The control condition was taken as reference of zero for this test, because no deviation implies that the hand path in an experimental condition was identical at the passing mark to the control hand path. As can be seen in Figure 3, we found that all @X-50, @X0, @X50, and @X100 conditions differed from control, all ps < 0.0021, while the @X-100 and @X150 conditions did not differ from control. All such departures in experimental conditions from the control condition were deviations away from the nontargets. Indeed, no evidence was found in any condition of deviation towards nontargets.

We have provided an additional heat map in Figure 4, which displays error at passing. These data were also analyzed with a RM ANOVA. We found a main effect for horizontal position, $F(5, 45) = 3.97$, $p < 0.01$, partial $\eta^2 = 0.81$. This indicates that the variability in movement trajectories was different for different horizontal nontarget locations. In addition, a main effect was found for vertical position, $F(3, 27) = 4.31$, $p < 0.025$, partial $\eta^2 = 0.95$, which suggests that movement trajectories had different levels of variability for different vertical positions. An interaction effect between horizontal position and vertical position for error at passing was not present.

There was a significant correlation between deviation at passing and error at passing scores, $r = 0.591$, $p < 0.01$, which implies that higher deviation scores were associated with higher error scores, see also Figure 5. The pattern for error at passing closely resembles the pattern described in the above for mean deviation at passing: Generally speaking, more obstructing nontargets elicited more variability over trials than less obstructing nontarget objects.

No association was found between the distance from the starting button (see Table 1) and summed deviation fraction (see Dependent measures and analysis section): There was no significant Pearson’s correlation, $r = -0.23$, $p > 0.05$. This suggests that closer nontargets were not associated with a stronger avoidance response.
However, we found a significant correlation between deviation and the angle (see also Table 1) of the nontarget relative to the starting button, $r = -0.80, p < 0.01$. This implies that when the angle toward nontargets (from the starting position) was more closely aligned with the straight ahead heading the associated avoidance response was stronger. Furthermore, we performed a backward stepwise linear regression analysis to test for the contribution of distance and angle parameters ($r_{angle, distance} = -0.06$) to summed deviation fraction. The analysis showed that a model with both angle and distance explained the most variability, with $r^2 = 0.84$. However, the contribution of the distance parameter was relatively small compared to that of angle: The change in $r^2$ for distance was 0.05 and for angle it was 0.79. The parameters $x$ position and $y$ position could not be included in this analysis because they were collinear with distance and angle ($r_{y, vector} = 0.93$ and $r_{x, angle} = 0.88, ps < 0.01$).

Interestingly, the relation between the strength of the avoidance response ($y$) and the angle toward the nontarget ($x$) can be described by the following function:

$$y = axe^{-|bx|}e^{-c}$$

This function describes obstacle avoidance as a function of obstacle angle, with $r^2 = 0.96$ see also Figure 6. To obtain this fit we used unconstrained non-linear minimization of the sum of squared residuals with respect to the various parameters ($a$, $b$, and $c$). What follows from this equation is that the avoidance responses are very strong for small angles from starting position toward the target and decrease quickly with larger angles, meaning that the hand is turned away from obstacles at a decreasing rate. The above equation is the obstacle term from Fajen and Warren’s dynamical model for obstacle avoidance during locomotion (Fajen & Warren, 2003). The explained variance of the fit function decreases to $R^2 = 0.80$ when the straight ahead angle ($0^\circ$) conditions are taken into account, as these evoke very strong, or near asymptotic, responses. Taken together, this implies that the angle between the (would be) direction of the hand and the direction towards the obstacle is the main determinant of avoidance behavior and that the obstacle acts as a repeller of the hand. Please note the asymmetry present in this relation, in that positive small angles give larger avoidance responses than negative angles.

**Reaction time**

We found no significant differences between conditions for reaction time.

**Movement time**

We found significant differences between horizontal position conditions for movement time, $F(5, 35) = 4.41$,
p < 0.01, partial $\eta^2 = 0.39$. Mean movement time with the nontarget @X-100 was 34 ms (± 2) slower than in the control condition, whereas it was 69 ms (± 3) slower for @X-50, 136 ms (± 4) slower for @X0, 122 ms (± 2) slower for @X50, 56 ms (± 2) slower for @X100, and 37 ms (± 2) slower for @X150. This indicates that longer movement time was needed to perform the reach when the nontarget was in the middle or medial compared to more lateral. We performed additional one-sample t tests to determine whether experimental conditions were different from the control condition. Results indicate that participants moved significantly slower in the experimental conditions than in the control condition, all (Bonferroni-corrected) ps < 0.05. Taken together with the absence of a systematic effect on speed-related measures, this seems to point toward a strategy where participants kept their movement speed constant across trajectories of different length (see below), which means that their movement times varied across conditions as a result. No further main effect or interaction effect was found for movement time.

**Grip aperture**

We found no significant differences between experimental conditions for grip aperture. This suggests that participants had a consistent grip aperture during the experiment and that they did not vary their grip aperture systematically as part of an avoidance response. This means that the deviation measures reported earlier (and measured using the index finger marker) are not confounded by grip aperture responses.

**Peak velocity**

We found no significant differences between conditions for peak velocity.

**Time to peak velocity**

We found no significant differences between conditions for time to peak velocity.

**Discussion**

The current study aimed to systematically map the effect of nontarget position in the workspace on reach to grasp movements. We used 24 different possible locations of the nontargets to determine the spatial consistency of avoidance responses. Our results show that the influence of each nontarget position on movement kinematics is specific. We demonstrated effects of horizontal position and vertical position of the nontarget on hand paths toward a target. The direction of our deviation effects were always away from nontargets and therefore we did not find evidence of any deviation towards nontargets. The avoidance responses to nontargets did not vary with distance from the start position to nontarget positions in the workspace. In addition, the angle toward the nontarget relative to the target seemed to determine the strength of the responses, with objects that are more medial in the workspace causing stronger veering movements. Although distance did not predict avoidance responses by itself, distance still affected avoidance responses in conjunction with angle. The relative contribution of distance, however, was marginal. Furthermore, we have also confirmed that the distribution of responses is not symmetrical across the workspace, that is, in this experiment we showed that right handed participants reacted more strongly to right side nontargets than left-side nontargets. So, although two given nontarget objects may be equidistant, the response to them may differ because of the side (in or out) of the reaching arm the nontarget is on. Taken together, these data imply that there is a fine-grained motor representation of nontarget position in the workspace.

We found interesting shifts in avoidance responses across space, as demonstrated by the absence of a relation between distance and avoidance and the complex relation between angle and avoidance. Accordingly, the obstructiveness of a nontarget is in a large part determined by the angle between the direction of the target and the direction of the nontarget, as this drives the avoidance response. This is in line with an empirically based model on obstacle avoidance in locomotion by Fajen and Warren (2003) where a similar relation (among others) between obstacle influence and angle to the obstacle is used to predict locomotion paths. Although the time scale and the reference frames in this experiment are quite different it is interesting to see that nontargets can function as repellers in a hand movement paradigm as well. Because we have not found an effect of distance on avoidance strength we interpret this as evidence supporting the representation of both obstructing and nonobstructing objects during motor planning. Otherwise, if only objects that were close to the hand would be represented, then there would have been an obvious shift in avoidance responses for nontargets that were closer to the hand compared to those further away from the hand.

The activity in visuomotor planning areas that is associated with objects present in the workspace may be thought of as an attentional landscape that denotes objects that are relevant for behavior (Baldauf &
Deubel, 2010). Movements are then executed toward the (highest) peak in the landscape and away from low(er) activity regions or valleys. Interestingly, Chapman, Gallivan, Culham, and Goodale (2011) have shown that there is top-down modulation of the early visual cortex when obstacles interfere with grasp planning. These authors found that the contralateral (to the reaching hand) posterior Intraparietal Sulcus (henceforth: IPS) is responsible for detecting objects that physically interfere with to-be-performed actions. In addition, it is responsible for suppressing the neural representation of obstructing objects in early visual cortex areas associated with visuomotor planning. Moreover, Chapman and colleagues found that the modulation of the visuomotor planning areas by the IPS was dependent on the degree of interference or obstruction afforded by the object. That is, the more the object obstructed the more activity was registered in IPS. The IPS thus reduces the activity of peaks in an attentional landscape to ultimately have the hand move away from obstructing objects while it travels toward the goal object. This process runs parallel to the top-down action selection process that determines the object that is grasped, which, according to Tipper et al. (1997), explains the deviating reaching behavior when objects are not obstructing. This explanation is based on the nervous' system inability to be completely selective during action planning. Behavioral biases are the result of competition between response codes within a distributed population of direction sensitive neurons. This is because if the response codes for the target and nontarget overlap, then the inhibition of nontarget related activity leads to inhibition of part of the activation for the target as well. The global vector that arises from the activation then points away from the nontarget, which is observed in the deviation of the trajectory of the hand away from the nontarget. According to Tipper et al. (1997) this occurs when the nontarget is not obstructing. However, data from Chapman et al. (2011) suggest that the IPS was only active when the object obstructed the planned movement, which implies that the severe reduction in early visual area activity via IPS is only present when nontargets obstruct movement. Although we have focused more on reaching, the study by Chapman et al. (2011) therefore provides a clear neural background for our findings: First, we see a decline in avoidance responses with increasing angle, which implies that the less obstructing a nontarget object is, the weaker the avoidance response is. This relation may be based on the decrease in IPS suppression associated with less obstructing nontargets. Moreover, this can also explain the differential response to ipsilateral and contralateral nontargets (relative to the reaching hand), as the ipsilateral objects obstruct the planned movement more: In bold strokes, in this experiment, the increased obstruction by nontargets led to increased IPS activity and in turn to a larger avoidance response away from the nontarget object.

We showed that nontarget objects lead to stronger avoidance responses when they are closer in depth and closer to the direct route to the target, as demonstrated by the vertical and horizontal nontarget position effects, respectively. This effect has been reported earlier by, e.g., Chapman and Goodale (2008) but never with many different locations of a single nontarget. Chapman and Goodale (2010) showed that avoidance responses were greater with one obstacle than with two obstacles. The fact that two obstacles were present in some studies means that the avoidance response in those cases might have been constrained. In bold strokes, the avoidance responses to a primary obstacle may have been smaller in order to properly avoid the secondary obstacle. We consider that although the magnitude of the avoidance response may have been smaller with two obstacles present, the direction of the effect is still quite systematic, i.e., away from the nontarget.

We speculated that movements veer more systematically around nontargets that are more obstructing because the movements around these targets require more stability or accuracy than movements around nontargets that are further away. This, however, does not resonate with our data as we find more stereotypical movements when nontarget objects are further away in horizontal and vertical position. Conversely, we find more variable movement once the nontarget is closer in horizontal and vertical position. The discrepancy between our hypothesis and our results can be explained by assuming that the required accuracy for an avoidance movement was not very high after all: The participants only needed to avoid knocking over the nontarget. In fact, the data suggests that it was not necessary for participants to control accuracy at all. Instead, movement speed was kept constant: We show that participants did not systematically vary speed during the experiment. An explanation may therefore be found in Fitts’s law (Fitts, 1954; Fitts & Peterson, 1964): Participants’ accuracy suffered in trials with longer (more curved) movement paths around more obstructing nontargets because they controlled the speed at which they moved. This supports findings by Vaughan, Barany, Sali, Jax, and Rosenbaum (2010) who showed earlier that Fitts’s law applies to three-dimensional obstacle avoidance movements. These authors also found that movement time increased with an increase of degree of obstruction by the obstacle. Vaughan et al. (2010) concluded that this result was congruent with Fitts’s law, which states that longer movement paths (around more obstructing obstacles) should lead to longer movement times.
A further explanation for the increased variability in evoked avoidance responses to nontargets that obstruct more can be found in the theory by Hamilton and Wolpert (2002). These authors predicted empirical avoidance trajectories with a model that minimized the probability of collision near the nontarget object as well as mean-squared error of position at the target location. This implies that probability of collision and position accuracy are important in planning obstacle avoidance movements. Hamilton and Wolpert (2002) also posited that variability in motor neuronal firing and variability in the motor unit recruitment pattern are sources of signal dependent noise in muscle force output (Hamilton & Wolpert, 2002). This means that when force output is increased, the size of the motor units recruited is also increased, which leads to larger variability in movement. Therefore, when stronger avoidance responses are required (the arm needs to be moved further sideways), then a larger muscle force output is required, which leads to more variability. This seems to be the case in our experiment.

In conclusion, we have mapped avoidance responses to a mesh of nontarget positions and have demonstrated that participants respond differentially across the vertical and horizontal dimension, where the strength of the response seems to be primarily driven by the angle between the target and nontarget. There is a hot region in the workspace where nontarget obstacles evoke the strongest avoidance responses and this region is mainly defined by obstacle positions with a direction that has small differences relative to the target direction. In other conditions where the angle and vertical distance is large, participants react stereotypically, so it seems these conditions can be lumped together with a normal reach-to-grasp movement. In all other instances the avoidance responses seem to follow a pattern that is predicted by a complex function. This finding indicates that there is no lumping together of conditions (other than obstructing vs. not obstructing) if the resolution of our experiment is as coarse as the physical size of the objects we used. That is, the grain in our experiment was the diameter of the nontarget objects. Therefore, the threshold for fine grained responses was 50 mm. We found that the resolution of the avoidance system is at least this size as each obstructing nontarget evoked a unique response. Moreover, the function we fit had a very large explained variance. Taken together, this may indicate that participants use a smooth scaling strategy to respond to obstacles either on foot (Fajen & Warren, 2003) or with their hands (this study). We therefore suggest that the spatial resolution of the nontarget location is fine grained, because responses are specifically tuned.

**Keywords:** perception and action, motor control, goal-directed movement

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**Footnotes**

1Unless specifically stated otherwise all spatial measures were computed from index finger marker data. Please also note that temporal measures are partly constrained by the refreshing frequency of the miniBird system (100 Hz), as movement onset was computed from processed position data. We calculated speed in each cardinal dimension (x, y, and z). These were used to define the beginning of the movement (Schot, Brenner, & Smeets, 2010). We determined movement onset by checking whether marker position was sufficiently close to the starting location (within a 3-mm radius), and whether the threshold for marker velocity (5 mm/ms) was exceeded for a sufficient number of samples (50 ms). A continuous function then expressed which of the candidate samples was actually closest to the threshold of e.g., minimal speed: $F_v = 1 - \frac{v}{v_{\text{max}}}$. 

2The size of the motor unit is related to how many muscle fibers are present in the motor unit; a large motor unit has many muscle fibers within it while a small motor unit has few muscle fibers within it.

**References**


