



# The effects of saliency on manual reach trajectories and reach target selection



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## ABSTRACT

Reaching trajectories curve toward salient distractors, reflecting the competing activation of reach plans toward target and distractor stimuli. We investigated whether the relative saliency of target and distractor influenced the curvature of the movement and the selection of the final endpoint of the reach. Participants were asked to reach a bar tilted to the right in a context of gray vertical bars. A bar tilted to the left served as distractor. Relative stimulus saliency was varied via color: either the distractor was red and the target was gray, or vice versa. Throughout, we observed that reach trajectories deviated toward the distractor. Surprisingly, relative saliency had no effect on the curvature of reach trajectories. Moreover, when we increased time pressure in separate experiments and analyzed the curvature as a function of reaction time, no influence of relative stimulus saliency was found, not even for the fastest reaction times. If anything, curvature decreased with strong time pressure. In contrast, reach target selection under strong time pressure was influenced by relative saliency: reaches with short reaction times were likely to go to the red distractor. The time course of reach target selection was comparable to saccadic target selection. Implications for the neural basis of trajectory deviations and target selection in manual and eye movements are discussed.

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## 1. Introduction

Efficiency in human vision and action is influenced by stimulus-saliency. Objects that stand out from the surrounding objects can automatically draw attention and consequently can be found much more easily than objects that are not unique and conspicuous. For example, think about looking for the full moon on a clear night, the goalkeeper in a soccer team, or a single red tulip in a field of yellow tulips. Whereas stimulus-saliency can benefit visual selection if it is in line with the search goal of an observer, stimulus-saliency can harm performance if it concerns an irrelevant distractor object; e.g., the moon can interfere with search for a star, the goal-keeper distract search for a specific defender and a red tulip delay selection for a certain yellow tulip. Experimental evidence for this has been found in studies of covert attention (Theeuwes, 1992, 1994; Yantis & Jonides, 1984) as well as in studies of overt visual selection. In overt visual selection stimulus-saliency has been demonstrated to affect performance in saccadic eye movements

(Godijn & Theeuwes, 2002; Theeuwes, Kramer, Hahn, & Irwin, 1998; van Zoest & Donk, 2006), saccadic trajectories (Godijn & Theeuwes, 2004; van Zoest, Donk, & Van der Stigchel, 2012; Walker, McSorley, & Haggard, 2006) as well as manual pointing movements (Kerzel & Schonhammer, 2013; Song & Nakayama, 2006; Welsh, 2011; Welsh & Elliott, 2004; Wood et al., 2011; Zehetleitner, Hegenloh, & Muller, 2011).

Visual saliency is thought to be represented in maps where objects compete for attention (Itti & Koch, 2001; Yantis, 2005) or more generally for behavioral priority (Baldauf & Deubel, 2010; Fecteau, Enns, & Kingstone, 2000). Critically, evidence suggests that the representations in priority maps changes as a function of time (Donk & van Zoest, 2008). This has been demonstrated in studies of covert attention (e.g., Donk & Soesman, 2010), saccadic selection (van Zoest & Donk, 2006; van Zoest, Donk, & Theeuwes, 2004) and in saccadic trajectories (van Zoest et al., 2012).

In the present study, we examine whether this dynamic competition between target and distractor is also revealed in the curvature of the reach trajectories and in the final endpoint selection of the reaching movements. Previous studies on reaching provide support for facilitation of selection by salient targets and disruption of selection by salient distractors, but have not investigated the time-course of facilitation and disruption simultaneously.

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### 1.1. Saliency in manual reaching

Evidence suggests that the efficiency of reaching movements increases with target saliency. For example, in a study by [Zehetleitner et al. \(2011\)](#) participants were instructed to reach a feature singleton in a search array on a touch screen. The feature singleton was either defined by luminance contrast, by orientation, or by both luminance and orientation contrast. The results showed that initiation times, total movement duration time as well as pointing accuracy were better for targets with high than for low feature contrast, and improved even further when targets were redundantly defined (i.e., targets combining two features).

Whereas salient targets can provide a benefit in manual reaching performance, salient distractors may result in a detriment in performance. [Kerzel and Schonhammer \(2013\)](#) provided evidence that reaches deviate toward salient distractors. They presented a search display when the reach response had already been initiated, forcing participants to decide where to reach while the movement was ongoing. Reach trajectories deviated toward the salient distractor, showing that competition between target and distractor in a visual search display is reflected in reach trajectories. While deviation toward a distractor was observed in this study, its saliency was not manipulated systematically. Instead, the distractor was always a red bar and the target was a tilted bar on a raster of vertically oriented bars. Thus, it is not clear whether a more salient distractor would more strongly attract reaching trajectories.

Further, [Wood et al. \(2011\)](#) found that salient distractors influence reaching behavior even in the absence of direct competition with the target. In their study, the start signal consisted of a beep and distractor stimuli. The distractors were presented on the left and right of fixation and varied in saliency. The start signal prompted participants to release the home button within 325 ms, and the target appeared only once participants had initiated the reaching movement. The target appeared on the left or right and had to be touched. The authors observed that the initial trajectories were biased towards the side of fixation that contained the more salient distractors despite that the distractors were presented before movement and target onset. The results moreover showed that a preview of 500 ms eliminated this saliency-induced bias.

### 1.2. Dynamic representations in performance

Psychophysical studies suggest that the impact of stimulus-saliency on performance is severely limited in time ([Donk & Soesman, 2010, 2011; Donk & van Zoest, 2008](#)). This work shows that saliency affects perceptual performance only when selection occurs very shortly after display presentation. Further support for the transient nature of stimulus saliency is provided in studies on overt saccadic selection. For example in a study by [van Zoest and Donk \(2005\)](#), participants were instructed to make an eye movement to an orientation singleton (i.e., a line tilted to the right) presented in a raster of vertically oriented line elements. In addition to the uniquely oriented target, a second singleton was presented that was also different in orientation from the non-targets (i.e., tilted to the left). The results showed that when target and distractor were equally salient, both elements were selected equally often when saccadic latencies were short, but eventually, as time between display onset and saccade latency increased, the target was selected more often than the distractor. In order to vary stimulus saliency, either the target was given a unique color or the distractor was given a unique color. Note that because the target was ultimately defined by orientation, color was task-irrelevant. Nevertheless, the results showed that color applied to the target resulted in more correct saccades to the target, whereas color applied to the irrelevant distractor resulted in more incorrect saccades to the

distractor (i.e., more 'capture' by the distractor). Importantly, the relative saliency of the elements affected performance only when the eye movements were initiated within 250 ms after display onset. After this time, the ability to select the correct target was not in any way influenced by the saliency of the elements (see also, [van Zoest et al., 2004, 2012](#)). Thus, evidence suggests that saccadic target selection is affected by the relative saliency of target and distractor specifically when processing of the display is limited in time.

Saccadic RT similarly was also shown to modulate deviations of saccadic trajectories ([Godijn & Theeuwes, 2004; van Zoest et al., 2012; Walker et al., 2006](#)). For example, results of [van Zoest et al. \(2012\)](#) showed that when stimulus-saliency was varied in terms of orientation contrast, saccades deviated more towards the more salient distractor than to the non-salient distractor; moreover, the difference in deviation as a function of distractor saliency was again observed only when saccades were initiated shortly after display presentation ([van Zoest et al., 2012](#)).

Looking into the time-course of manual motor representations, the literature reveals a comparably important role for time in reaching; however, the time-course in these studies is typically studied independently of relative stimulus-saliency. For example, [Cisek and Kalaska \(2005\)](#) showed that the motor system (i.e., the dorsal premotor area) first represents two competing target locations for selective reaching and only later the selection between them. Thus, the areas involved in the planning and execution of reaching movements do not necessarily reflect the final behavioral choice, but are linked to the dynamics of decision-making. Therefore, the trajectory of reaching movements may directly reflect competition between target and distractor representations. [Song and Nakayama \(2009\)](#) proposed that competition between choices is revealed in the early reach movement trajectories, thereby tracing the evolution of internal processing. In particular, reaches are initially directed to distracting stimuli (see also, [Tipper, Howard, & Houghton, 2000; Welsh & Elliott, 2004](#)) resulting in reach trajectories that deviate toward the distractor. As the conflict between the target and distractor is resolved, reaches home in on the correct goal. However, specifically how stimulus-saliency influence this time-course in manual reaching is yet unknown.

### 1.3. The present study

The aim of the present study was to investigate the time-course of the effects of saliency on reach trajectories and reach target selection. The present study is based on the same saliency manipulation as [van Zoest and Donk \(2005\)](#). Based on previous work on saccadic performance, we hypothesize that the influence of relevant and irrelevant stimulus-saliency will be limited to short-latency reaching responses. We predict that relative to the condition where target and distractor are equally salient, incidental target saliency will benefit short-latency reaching responses, whereas incidental distractor saliency will disrupt short-latency reaching responses. It is furthermore predicted that movements triggered later in time should not reveal any influence of incidental stimulus-saliency such that performance is expected to be alike across all three conditions.

In order to be able to specifically look at short-latency responses and increase the potential impact of stimulus-saliency (see also, [Hunt, von Mühlhagen, & Kingstone, 2007](#)) we reduced the allowable time to complete the manual movement (time limit) from Experiment 1 (1200 ms), to Experiment 2 (740 ms) to Experiment 3 (500 ms). In Experiment 4, we measured saccadic eye movements using the exact same parameters as in Experiments 1–3 to compare the time-course of manual reaching with the time-course of saccadic selection.

## 2. Experiments 1–3

Participants were asked to reach towards an orientation singleton tilted to the right (see Fig. 1A). In addition to a raster of non-targets, which were all vertical and gray, a line element tilted to the left was also present. This distractor had to be ignored. The main experimental manipulation concerned the color of target and distractor. In randomly interleaved conditions, (1) the distractor was red, (2) the target and distractor were both gray, or (3) the target was red. We predicted that curvature toward the distractor should be increased when the distractor was red and reduced when the target was red. Similarly, overt selection defined in terms of capture by the irrelevant distractor (e.g., Godijn & Theeuwes, 2002) was predicted to be low when the target was salient but high when the irrelevant distractor was salient. Moreover, effects of saliency on curvature and capture were expected to be strongest when response latencies were short and the difference between conditions was expected to disappear as reaction times increased. We not only evaluated curvature and capture as a function of RT, but also reduced the allowable time to complete the movement (time limit) from Experiment 1 to Experiment 3, which we expect to decrease overall RT and increase the impact of the distractor.

### 2.1. Method

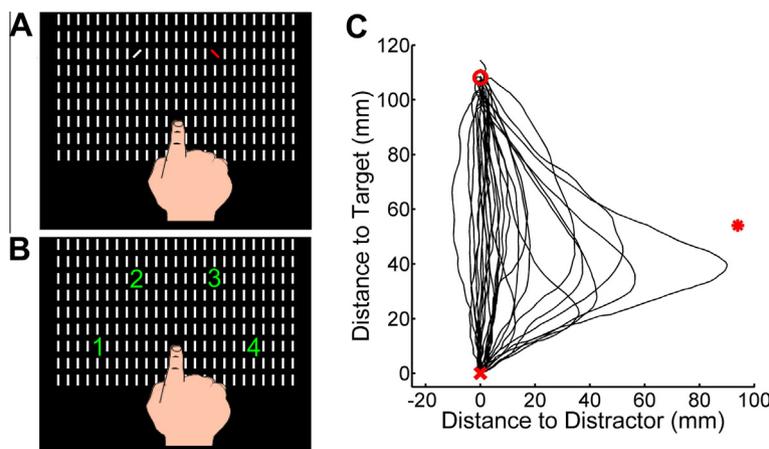
**Participants:** Psychology students at the University of Geneva participated for class credit. There were 14 participants in Experiment 1, 14 in Experiment 2, and 21 in Experiment 3. All reported normal or corrected-to-normal vision. The study was approved by the ethics committee of the Faculty of Psychology and Educational Sciences and was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki). Informed consent was given before the experiment started.

**Apparatus and stimuli:** The 3D coordinates of manual movements were recorded at a sample frequency of 150 Hz by means of a marker positioned on the nail of the right index finger (CMS20S, zebris Medical GmbH, Isny im Allgäu, Germany). The stimuli were presented on an 18 inch flat panel screen (60 Hz, 1280 × 1024 pixels) at a distance of ~40 cm between the center of the screen and the participant's eyes. One cm on the screen corresponded to ~1.4° of visual angle. Bars were placed in 25 columns and 9 rows with a center-to-center distance of 1.4 cm horizontally

and 2.4 cm vertically (see Fig. 1A). The bars had a width of 0.3 cm and a height of 1.5 cm. The central element in the third row was empty and corresponds to the initial position of the tip of the right index finger. The target was tilted by 45° to the right and the distractor was tilted by 45° to the left. In one-third of trials the target was uniquely colored red; in one-third of trials the target and distractor were both gray, and in one-third of trials the distractor was uniquely colored red. The context elements were gray and upright. Gray and red stimuli were isoluminant at 48 cd/m<sup>2</sup> and the background was black. Target and distractor elements appeared at 10.8 cm from the start position with an angular separation of 60°. Fig. 1B shows the four positions in which target or distractor could appear. When the target was presented at a central position, the distractor was presented equally often on the positions to the left or the right of the target. When the target was presented at the eccentric position, that is position 1 or 4, the distractor was presented on the only possible adjacent position, position 2 or 3, respectively.

**Procedure:** Participants started a trial by placing the right index finger on a square in the center of screen. After 500 ms, the square disappeared and the stimulus array was shown. Participants were instructed to reach the bar tilted to the right with their index finger while ignoring stimulus color. Participants were asked to respond as rapidly as possible while not making too many errors. Visual error feedback was given at the end of the trial. The hand had to be lifted from the screen and gliding on the screen was signaled as error. In each experiment, participants worked through 630 trials.

Note, as a result of placing the hand on the screen, it was not feasible to present target and distractor at six positions surrounding the fixation point as in the original study of van Zoest and Donk (2005). In order to not occlude either the target or the distractor by the hand, the target and distractor could appear in four different positions in the upper hemifield (cf. Fig. 1A and B). Target and distractor were always separated by 60° of rotation, resulting in six different target/distractor configurations. As shown in Table 1, the two eccentric positions had a lower probability of containing the target than the two eccentric positions (2/3 vs. 1/3). In addition, only the two central target positions had distractors on both sides. The eccentric target positions were included as filler trials to make all positions response-relevant, however, only the trials with targets on the central positions were analyzed for statistical significance. There are two reasons that motivate this selection of



**Fig. 1.** (A) Example stimuli (drawn to scale). The target is the bar tilted to the right. (B) The numbering of the four different target/distractor positions. (C) Sample data. Each line represents the trajectory of a single trial. Trajectories were rotated and mirrored such that the initial and final positions had an  $x$ -value of zero and deviations toward the distractor had positive  $x$ -values. The initial finger position was at  $x = 0, y = 0$ . The target would be at position  $x = 0, y = 108$  mm and the distractor at position  $x = 94, y = 54$  mm. Target and distractor were at the same distance from the initial finger position. The maximal lateral deviation was determined for each trajectory.

**Table 1**

Stimulus configurations and their probabilities in Experiments 1–3. The positions are illustrated in Fig. 1B. Configurations denoted by an asterisk are referred to as eccentric target positions and were not included in the analysis. Eccentric target positions (with targets on positions 1 or 4) were less likely than the central target positions (with targets on positions 2 or 3).

Position		Probability
Target	Distractor	
1*	2*	0.167
2	1	0.167
2	3	0.167
3	2	0.167
3	4	0.167
4*	3*	0.167

trials: first, the statistics and performance may be biased by the lower probability and imbalanced distribution of distractors. Second, the biomechanical constraints for reaches to the eccentric positions may differ from reaches to the central positions and further confound performance.

**Online performance criteria:** The following criteria were applied to provide feedback to the participants, but different criteria were used in the final analyses. In Experiments 1 and 2, the endpoint of the reach had to be within 2 cm of the center of the target bar, otherwise a choice error was reported to the participant. In Experiment 3, speed was emphasized and no feedback on the accuracy of the response was given. The allowable total time (reaction time + movement time) was 1200 ms in Experiment 1, 740 ms in Experiment 2, and 500 ms in Experiment 3. The criterion of 740 ms corresponds to the fastest individual RT observed in Experiment 1, and 500 ms was too short to complete the movement reliably, resulting in many choice errors. Feedback about slow responses was given on 1.6%, 14%, and 37% of the trials in Experiments 1–3, respectively. RTs shorter than 0.1 s were reported as anticipations.

## 2.2. Data treatment

On- and offsets of the movements were recalculated after low-pass filtering the velocity traces at 35 Hz. The start of the movement was determined by a velocity criterion of 150 mm/s. The end of the movement was determined when the finger approached the screen surface and the distance was less than 3 mm relative to the baseline before the movement. The time from target to movement onset was considered RT.

To determine whether **movement endpoints** deviated toward the distractor, we rotated the trajectories by a fixed amount that depended on the target location. Half of the trajectories were flipped horizontally so that positive and negative  $x$ -values indicated a deviation toward and away from the distractor, respectively. The mean endpoints across observers were less than one millimeter away from the target position and were not analyzed any further.

To determine whether the **curvature of movement trajectories** deviated toward the distractor, we rotated the trajectories so that start- and endpoints had an  $x$ -value of zero (cf. Fig. 1C). Half of the trajectories were also flipped horizontally so that positive and negative values indicated deviations toward and away from the distractor, respectively. The maximum curvature of a trajectory was simply the largest deviation from zero on the  $x$ -axis. The sign of the curvature was retained in the analysis of maximal curvature.

The following trials were removed in the indicated order. (1) Trials with missing samples. (2) Trials with maximal curvature larger than the horizontal distance between target and distractor after rotation (9.4 cm, see Fig. 1C). (3) Trials with RTs faster than 100 ms. (4) Trials with reaction times and (5) trials with movement

times slower than the condition mean plus 2.5 times its standard deviation.

The Euclidian distance between target and distractor was 108 mm. Movements closer than 54 mm to the target were categorized as having reached the target and movements with a distance smaller than 54 mm to the distractor as having reached the distractor. Generally, reaches to the target were very precise. The mean standard deviation of endpoints for reaches to the target was 3.9, 4.2, and 6.7 mm in Experiments 1–3, respectively. The mean standard deviation for reaches to the distractor was 22.9, 20.8, and 11 mm, respectively.

We divided the data into five quintiles according to RT, from the fastest to the slowest RT. To avoid spurious effects of outliers, we chose the median as a measure of the central tendency, but similar results were obtained with means. Three-way, mixed-factors, within-subjects ANOVAs were carried out (3 experiments  $\times$  3 distractor conditions: distractor red, both gray, target red  $\times$  5 quintiles). As it only reflects the ordering of the RTs, the effect of quintile on RTs will not be reported. The Greenhouse–Geisser correction of degrees of freedom was applied where appropriate.

## 2.3. Results

In Experiment 3, 21 students participated, but the data of six was discarded: for three participants, more than 35% of the trials had missing samples. Another three participants ignored the time constraint and accepted a high percentage of time-out errors (69%, 74%, and 93%) while making few choice errors (3%, 4%, and 4%) in violation of the instructions.

The total percentage of excluded trials was 10.2%, 8.1%, and 12.6% in Experiments 1–3, respectively. Excluded trials were accounted for by missing samples (5.9%, 1.9%, 6.4%), extreme curvature (0.2%, 0.3%, 0.1%), anticipations (0.7%, 2.0%, 1.3%), long reaction times (1.4%, 1.3%, 1.3%), and long movement times (2.2%, 2.9%, 2.7%).

Reaches went neither to the target nor to the distractor in 0.2%, 0.04%, and 1.0% of the trials in Experiments 1–3, respectively. Trials with targets on the eccentric positions were not analyzed (see Section 2.1).

**Manual reaction time:** Only trials that went to the target were included. The ANOVA (3 experiments  $\times$  3 distractor conditions  $\times$  5 quintiles) on median RTs showed that RTs decreased from Experiment 1 to Experiment 3 (381, 313, and 283 ms, respectively),  $F(2,40) = 7.5$ ,  $p = .002$ , which reflects the successively shorter time limit (1200, 740, and 500 ms, respectively). RTs were affected by distractor condition,  $F(2,80) = 12.31$ ,  $p < .001$ . In line with our hypotheses about curvature, RTs were slower when the distractor was red (329 ms), intermediate (326 ms) when both were gray, and shorter when the target was red (322 ms), but the differences were very small. The interaction of distractor condition and experiment approached significance,  $F(4,80) = 2.28$ ,  $p = .067$ , showing that saliency did not have an effect in Experiment 2 (312, 314, and 311 ms for distractor red, both gray, and target red, respectively), whereas it did in Experiments 1 and 3. The interaction of RT quintile and experiment,  $F(2,3,45,6) = 3.38$ ,  $p = .037$ , showed that the RT distribution was broader in Experiment 1 (from 303 to 466 ms) than in Experiment 2 (from 251 to 378 ms) or Experiment 3 (from 219 to 353 ms), which may be explained by the less stringent time limit in Experiment 1. No other effects approached significance.

**Maximal curvature:** Only trials that went to the target were included. Mean maximal curvature (of individual median values) as a function of distractor condition and RT quintile is shown in Fig. 2.

The ANOVA on data from the central target positions showed that maximal curvature was smaller with strong time pressure in

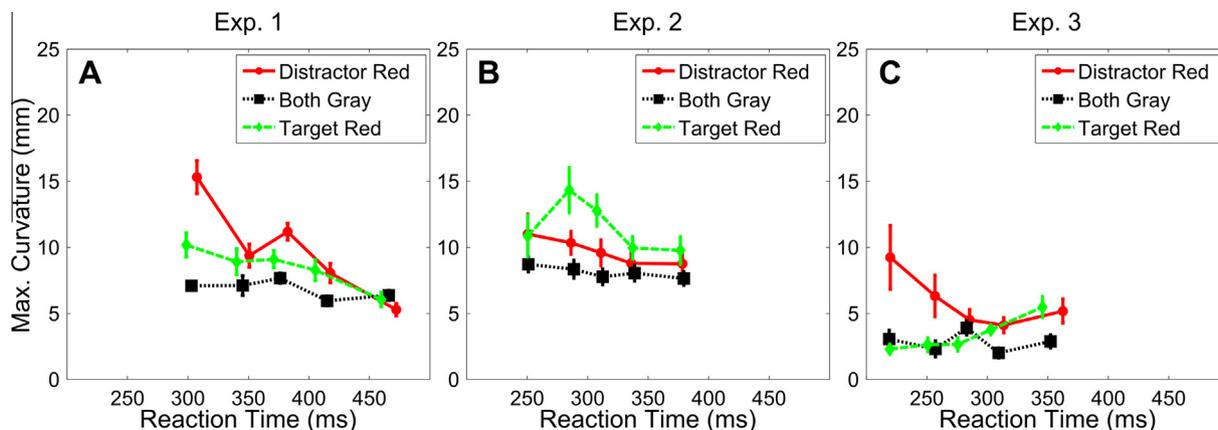


Fig. 2. Results from Experiments 1–3 are shown in panels A–C, respectively. Mean maximal curvature is shown as a function of distractor condition and reaction time quintile. Error bars show the standard error of the mean.

Experiment 3 (4.0 mm) than with light time pressure in Experiment 1 (8.4 mm) or moderate time pressure in Experiment 2 (9.8 mm),  $F(2,40) = 6.67, p = .003$ . The effect of distractor condition approached significance,  $F(1.4,55.2) = 2.98, p = .077$ , but was not consistent with our hypotheses. Maximal curvature was about equal when the distractor (8.5 mm) or the target (7.8 mm) was red and reduced when both were gray (5.9 mm). The effect of RT quintile was significant,  $F(2.4,97.0) = 4.11, p = .014$ , showing that maximal curvature decreased slightly by 2 mm from the fastest to the slowest RT quintile (8.6, 7.7, 7.7, 6.6, 6.4 mm, respectively). No other effects approached significance. In particular, the effect of quintile was not modulated by the distractor condition,  $F(3.4,6.9) = 1.88, p = .127$ , showing that the decrease in curvature with increasing RTs was not stronger when the distractor was red. We had expected large curvature with short RTs in this condition. Separate ANOVAS (3 distractor conditions  $\times$  5 quintiles) for each experiment confirmed the absence of interaction,  $ps > .184$ . With the short time limit in Experiment 3 (cf. Fig. 2C), it looks as if the maximal curvature increased for short RTs, however, the higher means in this condition were caused by a single participant with extreme curvature (74.3 mm) in the first quintiles. The increased variability due to this participant is visible in the large error bars.

**Capture:** Trials that went to the target, the distractor, or another position and met the criteria enumerated above were included. Fig. 3A shows the mean percentage of trials that went to the distractor (capture) in Experiment 3. The data from Experiments 1

and 2 are not shown for lack of significant results. The ANOVA showed that the percentage of capture was low in Experiments 1 and 2 (2.3% and 4.7%, respectively), but increased in Experiment 3 (25.9%),  $F(2,40) = 64.71, p < .001$ , confirming that strong time pressure and emphasis on speed resulted in many reaches toward the distractor. All remaining main effects and interactions were significant or approached significance,  $ps < .075$ , including the three-way interaction of experiment, distractor condition, and quintile,  $F(9.9,197.5) = 2.36, p = .012$ . Therefore, separate two-way ANOVAs (distractor condition  $\times$  quintile) were carried out for each experiment. The ANOVAs on the data from Experiments 1 and 2 did not yield any significant results. However, the ANOVA on the data from Experiment 3 confirmed our hypothesis. More reaches went to the distractor when the distractor was red than when the target was red (31.4% vs. 20.4%) and when both were gray, the percentage was intermediate (25.9%),  $F(1.2,17.2) = 6.54, p = .016$ . Importantly, the effect of quintile,  $F(4,56) = 5.76, p = .001$ , was modulated by distractor condition,  $F(8,112) = 2.92, p = .005$ . When the distractor was red, the percentage of capture with short RTs was high and decreased with increasing RT (37.8%, 38.1%, 31.6%, 27.5%, 22.0%, respectively), as confirmed by a one-way ANOVA,  $F(4,56) = 8.49, p < .001$ . The percentage of reaches to the distractor did not change across RT quintile when both were gray,  $F(4,56) = 1.37, p = .255$ , or when the target was red,  $F(4,56) = 1.99, p = .108$ . Thus, reaches with short RTs were captured by the red distractor and capture decreased with slower RTs. The other two conditions did not show changes in capture as a function of RT.

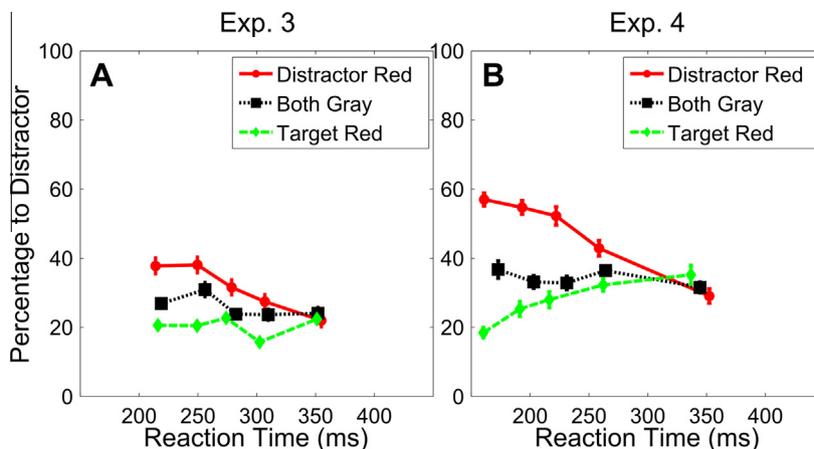


Fig. 3. Results from Experiments 3 and 4 are shown in panels A and B, respectively. The mean percentage of responses (left: reaches, right: saccades) to the distractor is shown as a function of distractor condition and reaction time quintile. Error bars show the standard error of the mean.

**Table 2**

Mean maximal curvature (in mm) for the central positions in Experiments 1–3 and the results of *t*-tests comparing the means to zero. By Bonferroni correction, the critical *p*-value is .0167 with three *t*-tests per experiment.

	Mean	<i>t</i> -Value	<i>df</i>	<i>p</i> -Value
Experiment 1				
Distractor red	9.8	8.32	13	<.001
Both gray	6.8	9.52	13	<.001
Target red	8.5	6.51	13	<.001
Experiment 2				
Distractor red	9.7	4.43	13	=.001
Both gray	7.1	7.26	13	<.001
Target red	11.5	4.88	13	<.001
Experiment 3				
Distractor red	5.9	2.4	14	=.031
Both gray	2.8	3	14	=.010
Target red	3.4	3.9	14	=.002

## 2.4. Discussion

Experiments 1–3 yielded at least five main findings. First, there was a small effect of saliency on RTs confirming that saliency facilitated or hampered visual search depending on whether the target or the distractor was salient. Second, the results confirmed that reaching trajectories curved toward the distractor, and separate *t*-tests against zero showed that this effect was reliable in all conditions (cf. Table 2). This finding supports the idea that simultaneous action plans to target and distractor are created and compete for final selection (Cisek & Kalaska, 2005; Song & Nakayama, 2009). Consistent with a growing literature on reaching movements, trajectories deviated toward competing non-target elements (Buetti & Kerzel, 2009; Finkbeiner, Song, Nakayama, & Caramazza, 2008; Kerzel & Schonhammer, 2013; Scherbaum, Dshemuchadse, Fischer, & Goschke, 2010; Song & Nakayama, 2006; Welsh, 2011; Wood et al., 2011). Third, the deviation toward the distractor did not depend on relative target saliency, which is contrary to our expectation that the deviation should be larger when the distractor was red than when the target was red. Fourth, we did not observe the expected time-course of the deviation toward the distractor. Specifically, the analysis of maximal curvature as a function of RT did not show that curvature was strongest when RT was short. In addition, curvature did not increase as RTs successively decreased with the stricter time limits across experiments. Quite to the contrary, very rapid movements in Experiment 3 produced smaller deviations toward the distractor than less rapid movements in Experiments 1 or 2. Fifth, effects of saliency were visible in manual target selection when strong speed pressure was applied (Experiment 3). That is, when participants were forced to respond very quickly, reaches were captured by the distractor more frequently when the distractor was salient than when the target was salient, which is consistent with previous studies on saccadic target selection (van Zoest & Donk, 2005).

Overall, our results suggest dissociation between reach trajectories and reach target selection. Whereas reach trajectories were not affected by the relative saliency of target and distractor, reach target selection was affected. In addition, the transient time course of saliency-driven influence was only visible in reach target selection.

## 3. Experiment 4

We observed that the pattern of results for reach target selection under time pressure was similar to previous observations on saccadic target selection. To understand whether the magnitude of capture or its time course was comparable between saccades and reaching, we measured saccadic eye movements using the exact same parameters as in Experiments 1–3. Instead of reaching

towards the target, observers in Experiment 4 were instructed to make a saccadic movement to the line tilted to the right with an emphasis on speed. We expect to replicate the results of van Zoest and Donk (2005), who reported that short-latency saccades are more likely directed at the red element, irrespective of whether it is the target or distractor, whereas long-latency saccades are directed at the target, independent of stimulus-saliency. We analyzed capture of saccadic responses (Experiment 4) together with capture of manual reaches (Experiment 3).

### 3.1. Method

Eye movements were recorded by means of an EyeLink 2 eye tracker (Osgood, Ontario, Canada) in pupil only mode at 250 Hz. A 9-point calibration was run before the experiment started and every 90 trials during the experiment. Before each recalibration, a short break was administered and the head-mounted eye tracker was taken off. Observers were instructed to make a speeded saccade to the line tilted to the right. As in van Zoest and Donk (2005), no error feedback was given. The head was stabilized by a chinrest at ~40 cm from the center of the screen. Fifteen students participated.

### 3.2. Results

We determined the angle of the first saccade (i.e., the vector between saccade start and endpoint). If it was within  $\pm 30^\circ$  of the vector between fixation location and target, it was counted as a saccade to the target. We considered this approach appropriate because the eccentricity of the targets was rather large ( $\sim 8^\circ$ ) and observers were likely to make more than one saccade to reach the target. The data from three participants was discarded because more than 40% of their trials were directed neither at the target nor at the distractor, which is most likely due to slippage of the head-mounted eyetracker. Trials with recording errors (2.8%), RTs shorter than 50 ms (7.8%) and longer than the condition mean plus 2.5 times the respective standard deviation (2.7%) were removed from analysis. Overall, 13.3% of the trials were excluded from analysis. In 6.2% of the trials was the saccade directed neither at the target nor at the distractor.

*Saccadic reaction time:* Because of the large number of capture trials in Experiment 4, trials were included when they went to the target, the distractor, or another position and met the criteria enumerated above. The ANOVA (2 experiments, 3 distractor conditions, 5 quintiles) showed that RTs tended to be shorter with saccadic than with manual responses by 43 ms (238 vs. 281 ms),  $F(1,25) = 3.66$ ,  $p = .067$ . The effect of distractor,  $F(2,50) = 13.79$ ,  $p < .001$ , showed that RTs were slightly longer with a red distractor than a red target (259 vs. 256 ms), but RTs when both were gray were not intermediate, but longer than the two conditions with a salient element (263 ms). The interaction of quintile and experiment approached significance,  $F(1.2,30.9) = 3.01$ ,  $p = .085$ , suggesting that the distribution was wider with saccades (from 165 to 344 ms) than with reaching movements (from 219 to 353 ms). Finally, the interaction of distractor condition and quintile was significant,  $F(3,3,83.1) = 3.81$ ,  $p = .010$ , but there was no obvious interpretation. From the fastest to the slowest quintile, mean RTs were 187, 221, 250, 283, 354 ms when the distractor was red, 196, 230, 257, 287, 348 ms when both were gray, and 188, 220, 245, 282, 344 ms when the target was red.

*Capture:* Trials that went to the target, the distractor, or another position and met the criteria enumerated above were included. The mean proportions of capture trials are shown in Fig. 3. A mixed-factors, three-way analysis of variance showed that more capture occurred with saccades in Experiment 4 than with reaching movements in Experiment 3 (36.4% vs. 25.9%),  $F(1,25) = 8.47$ ,  $p = .007$ .

The effect of quintile,  $F(4,100) = 4.71$ ,  $p = .002$ , was modulated by distractor condition,  $F(4.2,105.4) = 7.97$ ,  $p < .001$ , which is consistent with the expected time-course. Separate one-way ANOVAs (5 quintiles) were carried out for each distractor condition. Capture decreased with increasing RT quintile when the distractor was red (47.4%, 46.4%, 41.9%, 35.2%, 25.5%, respectively),  $F(2.6,69.2) = 17.72$ ,  $p < .001$ . It remained stable when both were gray (31.8%, 32.1%, 28.3%, 30.1%, 27.8%, respectively),  $F(2.2,57.1) = 1.92$ ,  $p = .113$ , and when the target was red (31.3%, 31.9%, 27.8%, 29.3%, 27.4%, respectively),  $F(4,104) = .86$ ,  $p = .489$ . The three-way interaction between experiment, distractor condition, and quintile did not reach significance,  $F(4.2,105.4) = 1.87$ ,  $p = .117$ , suggesting that the transient effect of saliency was similar for saccades and reaching.

### 3.3. Discussion

Our results replicate those of [van Zoest and Donk \(2005\)](#) for saccadic eye movements and confirm that the time course of capture in overt selection is similar for saccades and reaching. More saccades and reaches went to the target when it was red than when the distractor was red. The bias to move to the red element decreased with RT quintile: in the fastest RT quintile, responses went to the distractor when it was red, but in the slowest RT quintile, the majority of the saccades went to the target. However, the main effect of experiment also showed that the magnitude of capture was smaller with reaching movements than with saccades. It is telling that we did not enforce a strict time limit with saccadic eye movements, but nevertheless many capture trials occurred. The analysis of RTs suggests that even the spontaneous latencies of saccades in Experiment 4 tend to be shorter than the forced rapid reaches in Experiment 3.

## 4. General discussion

The aim of the present study was to investigate the time-course of the effects of saliency in manual reaching. In the present experiments, relevant and irrelevant saliency was varied using color: either the target was a color singleton or an irrelevant distractor was a color singleton. It was predicted that relevant target saliency would benefit selection whereas irrelevant distractor saliency would hamper selection ([van Zoest & Donk, 2005](#); [van Zoest et al., 2004](#)). We evaluated this hypothesis with respect to three dependent variables: RT, curvature, and capture. The analysis of RTs suggested that larger saliency of the target facilitated responses whereas larger saliency of the distractor slowed performance, but this result was observed in two experiments out of four only (in Experiments 1 and 3, but not in 2 and 4). In the analyses of reaching trajectories, no systematic evidence was found that increased saliency led to more curvature and that this effect was strongest at short latencies. However, we confirmed that reaches deviated toward the distractor, albeit irrespective of saliency. The analysis of capture by the distractor showed that with increased time pressure, there was more capture when the distractor was salient. In addition, the time course of capture was consistent with our hypothesis that the effect of saliency is short-lived and only concerns fast responses.

### 4.1. Models accounting for trajectory deviations

To explain trajectory deviations reference is typically made to competitive interactions between movement vectors in a spatiotopic activation map ([McPeck, 2006](#); [Tipper, Howard, & Jackson, 1997](#); [Tipper et al., 2000](#); [Van der Stigchel, Meeter, & Theeuwes, 2006](#)). When the competition between two movement vectors that sep-

arately represent a target and distractor remains unresolved, the residual activity at the distractor location may cause the weighted average to be directed in the direction of the distractor (e.g., [McPeck, 2006](#)). Thus, an irrelevant distractor may cause the final movement to deviate towards this element. Deviation is typically found to decrease as a function of latency and this is thought to reflect the developing inhibition of the movement vector to the irrelevant distractor and resolving conflict resolution between target and distractor. In fact, inhibition of the irrelevant activation at the distractor location may cause distractor-related activity to drop below baseline. Subsequently, the integration of distractor inhibition into the calculation of the movement program to the target may cause the final vector to be directed away from the inhibited distractor location in saccadic movements ([Mulckhuysse, Van der Stigchel, & Theeuwes, 2009](#); [Tipper et al., 1997](#); [Walker et al., 2006](#)).

In the present experiment, looking at manual movements, the movement deviation observed was solely in the direction and towards the irrelevant distractor (see also, [Buetti & Kerzel, 2009](#); [Welsh, 2011](#); [Welsh & Elliott, 2004](#)). There was no evidence for deviation away. As the conflict between the target and distractor was resolved, the curvature towards the distractor decreased but never seemed to drop below baseline. In addition to this dissimilarity between manual curvature and saccadic curvature, a second dissociation was found in the absence of a modulation by stimulus-saliency in reach trajectories. While the present results confirm that manual movements deviate toward distracting stimuli, modulations of trajectories by saliency may only be present for saccades ([Godijn & Theeuwes, 2004](#); [van Zoest et al., 2012](#)). The present study showed that saliency did not bias reaching trajectories, but had an effect on target selection with rapid movements.

### 4.2. A neural dissociation?

The present study shows that the effect of saliency is different for reach target selection and reaching trajectories. At the same time, the results reveal that the effects of saliency on manual and saccadic target selection are similar. How can this dissociation be explained? One admittedly speculative answer is the distinction between a more abstract, effector-independent priority map and effector specific planning and execution. Recently, [Song, Rafal, and McPeck \(2011\)](#) suggested that the superior colliculus (SC) is involved in both saccadic and manual target selection. They observed that inactivation of the SC did not disrupt the execution of hand movements as such, but did strongly affect target selection for reaching movements. This is surprising as the SC is known to be part of a network for oculomotor control comprising the frontal eye fields, the lateral intraparietal areas, and the supplementary eye fields ([Goldberg, Bisley, Powell, Gottlieb, & Kusunoki, 2002](#); [Gottlieb, Kusunoki, & Goldberg, 1998](#); [McPeck, Han, & Keller, 2003](#); [McPeck & Keller, 2001](#); [Schall & Thompson, 1999](#); [Thompson & Schall, 1999](#)). In contrast, target selection for reaching has previously been associated with dorsal premotor area and the parietal reach region ([Cisek & Kalaska, 2005](#); [Song & McPeck, 2010](#); [Song, Takahashi, & McPeck, 2008](#)). However, the deficits in manual target selection following inactivation of the SC suggest that the SC is involved in target selection for both effectors and is therefore concerned with rather abstract decision-making. Thus, the shared effects of saliency on target selection for hand and eye movements may originate in the effector-unspecific neurons of the SC. In contrast, the modulation of saccade curvature by saliency ([van Zoest et al., 2012](#)) may arise in ocular neurons of the SC. The absence of trajectory deviations in reaching may be accounted for by the fact that planning and execution of manual movement is controlled almost exclusively by cortical areas ([Cisek & Kalaska, 2005](#); [Scherberger & Andersen, 2007](#)).

#### 4.3. Different latencies of saccades and reaching movements

A study by Hunt et al. (2007) is very similar to ours in that they observed capture by a distracting stimulus only when participants were encouraged to respond very rapidly. Their study used the additional singleton task where participants were instructed to localize a unique color singleton. In the eye movement block, participants were instructed to make a saccadic eye movement to this target. In the manual movement block, participants were instructed to manually direct the joystick towards the location of the unique singleton. In half of the trials, an additional sudden onset was presented simultaneous to the presentation of the search display. The results initially showed that the onset had a distinct influence on eye and manual responses; whereas eye movements were directed towards the sudden onset on about 30% of trials, manual joystick responses were almost never directed towards the sudden onset. However, critically, the results also showed that the manual responses were much slower than eye movements. In fact, the reaction time distributions barely overlapped with one another in this context (Hunt et al., 2007). In a second experiment, Hunt et al. imposed reaction time deadlines on the responses in order to bring the reaction time distributions more closely in line with one another. Indeed, when the distributions were more closely aligned, manual responses began to be directed toward the onset at a similar rate as for eye movements: fast eye and manual responses were directed towards the sudden onset distractor, and slower eye and manual responses were directed towards the target. The authors concluded that the effect of the distractor on target localization was shared across response systems and critically depends on a shared time-course. With respect to the results of the present study, comparison of Experiments 1 and 2, which featured moderate time limits, and Experiment 3, which was close to saccadic reaction time in Experiment 4, confirms their conclusion.

#### 4.4. Continuous tracking of decision making

One further possibility of why the present study may have had troubles finding systematic evidence for an effect of saliency in reaching trajectories may be because of methodological issues. The present study used a common stimulus–response paradigm, where the response was initiated only after the stimulus had been presented. In some previous studies, the stimulus was presented while the movement was ongoing (Chapman et al., 2010; Kerzel & Schonhammer, 2013; Wood et al., 2011). Specifically, the target was not presented until participants had released a button that signaled the start of the movement. This manipulation ensured that the planning of the movement occurred online as the movement was already underway when the target was presented. In the present study, the visual display was presented prior to the initiation of the movement. This allowed observers to control when to make the movement and allowed for a more careful planning stage. It is likely that this latter circumstance benefitted correct selection for the target and potentially constrained the impact of saliency on trajectories. While this could be regarded as a limitation of the present experiment, the motivation for the present study was precisely to investigate the time-course of saliency in reaching movements initiated under the control of the observer. While presenting the display contingent to a movement signal may have increased the relative impact of stimulus-saliency, it would not have allowed insight into the continuous development of the representation of stimulus-saliency as a function of reaction time.

#### 4.5. Eye movements

Previous research has shown that there is close temporal (Adam, Buetti, & Kerzel, 2012; Prablanc, Echalié, Komilis, & Jeannerod, 1979) and spatial (Sailer, Eggert, & Straube, 2002; Song & McPeck, 2009) coupling between saccades and reaching movements. Because we did not measure eye movements in Experiments 1–3, we cannot rule out that the close coupling between the two effectors contributed to the pattern of results. However, we think it is unlikely. First, effects of salient distractors on reaching movements were measured with and without monitoring of eye movements and no difference were observed (Kerzel & Schonhammer, 2013). Second, the capture of reaching movements in Experiments 1 and 2 was basically absent and did not follow the time course of saccades in Experiment 4. If the eye movements had biased reaching movements, we would expect a similar pattern of results in Experiments 1 and 2 as in Experiment 3, which was not the case. Thus, we think that eye movements are unlikely to account for the results observed in reaching movements.

### 5. Conclusions

Overall, our results show that reaching movements are biased toward distractors. However, the relative saliency of target and distractors does not affect reaching trajectories. In contrast, manual target selection was affected by relative saliency, quite similar to saccadic target selection. We suggest that target selection in saccades and reaching movements may share neural structures, which explains why saliency has similar effects in both effectors. In contrast, the competition between target and distractor that is reflected in reach trajectories may not originate from the same neural structure that contributes to target selection.

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