The visual attractor illusion

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In many visual illusions, the perceived features of an object such as its size or orientation are influenced by nearby objects. In contrast, the presence of nearby, static objects often enhances the perceived spatial location of another object. Here we present a type of visual illusion in which the presence of a static object alters another object's perceived location. Participants localized the edge of a briefly presented and masked target object. Localization was accurate when the masked target was presented in isolation. However, when another nearby object was presented at the same time as the target, localization deviated toward the nearby object (the "attractor"). This "visual attractor illusion" was stronger when the attractor object was task-relevant rather than irrelevant and diminished as the experiment progressed, suggesting that it was modulated by attention. Visual transients also play an important role in the illusion, which depends on the sudden onset of the attractor object and backward masking of the target. We suggest that the brief appearance of an object (the attractor) distorts perceptual space and draws in the perceived location of a neighboring object. Alternatively, localization of a masked target may be weighted toward the position of a concurrently presented visual transient.

Keywords: visual illusions, localization, attention

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Introduction

Many visual illusions are produced when an object's immediate surrounding alters its perceived features. For example, some geometrical illusions emerge because the perceived size of an object is changed through assimilation or contrast with the size of surrounding objects (Jaeger, 1999). Such surrounding effects have been reported for perceived orientation, contrast, brightness, shape, motion, and facial expressions (Palmer, 1999; Sweeny, Grabowecky, Paller, & Suzuki, 2009). It is believed that surrounding illusions result from the interactions of neighboring neurons, as stimuli presented outside of a neuron's receptive field often affect its firing rates (Eagleman, 2001; Zipser, Lamme, & Schiller, 1996).

In contrast to the perception of nonspatial features, perceptual localization is relatively accurate (Eurich & Schwegler, 1997). In addition, localization is often improved, rather than impaired, by surrounding objects, possibly because surrounding objects provide a spatial reference frame for the target object (White, Levi, & Aitsebaomo, 1992). Mislocalizations have been reported, however, particularly for displays involving moving stimuli. For example, in the Fröhlich effect, observers tend to mislocalize motion onsets and offsets in the direction of the motion (Fröhlich, 1923; Kerzel, in press). A similar bias is found in the slit illusion in which a circle moving behind a slit is perceived as compressed along the trajectory of its motion (i.e., it is perceived to be an oval; Aydın, Herzog, & Öğmen, 2008). In addition, memory for the final position of a moving target can be shifted toward a briefly presented distractor object (Kerzel, 2002a). Finally, in the flash-lag effect, a stationary stimulus flashed concurrently with a moving stimulus is perceived as lagging behind the moving stimulus (Mackay, 1958; Metzger, 1932; Nijhawan, 1994). Although the underlying mechanism for the flash-lag effect is still being debated, many researchers assume that it depends on the integration of motion signals over time (Eagleman & Sejnowski, 2000; Roulston, Self, & Zeki, 2006).

Unlike moving stimuli, static objects rarely distort the perceived location of neighboring stimuli. Any influence static objects may have on localization appears to be restricted to the remembered rather than the perceived location of neighboring stimuli. For example, the remembered location of an object is shifted toward a salient, stable perceptual landmark (Nelson & Chaiklin, 1980; Sadalla, Burroughs, & Staplin, 1980), and this memory bias increases at longer memory delays (Sheth & Shimojo, 2001). Furthermore, a stationary object was found to bias spatial memory, but only when a comparison stimulus was presented before or after, but not concurrently with, a peripheral target (Bocianski, Müsseler, & Erlhagen,

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2008). Similarly, Kerzel (2002b) found that the remembered location of a peripheral target was biased away from a distractor only when the distractor was presented throughout a trial or was briefly presented during a retention interval, but not when the items were presented together. Thus, it remains unclear whether static objects can distort the perceived (as opposed to remembered) location of a co-occurring neighboring object.

Here, we report a visual illusion in which the perceived location (rather than a nonspatial feature of the object) of a briefly presented and masked object is distorted by a concurrently presented, nonmoving, object—the "attractor." When a target object is briefly flashed at the same time as a second object, the perceived location of the target object deviates toward the other object, an effect we call the *visual attractor illusion (VAI)*. This effect cannot be attributed to poor localization in general because the target object is accurately localized in the absence of the attractor. We report a series of experiments that establish the basic effect, its relationship to attention, and its dependency on visual transients. In the General discussion section, we compare this illusion with previously reported illusions and discuss its underlying mechanisms.

Experiment 1: The visual attractor illusion (VAI)

The purpose of Experiment 1 was to establish and quantify the basic VAI. Participants localized the left (or right) edge of a briefly presented and masked outline square (*target*). The target either appeared in isolation (*attractor absent*) or concurrently with another object (*attractor present*). Preliminary observations revealed that when targets overlapped with a mask and an attractor was present, the target appeared to deviate toward the attractor. The illusory percept of seeing the target as closer to the attractor was much weaker or absent if the target did not spatially overlap with the mask. To quantify these phenomenological impressions, this study focused on trials in which the target and the masks overlapped. The visual attractor illusion was measured as the difference in localization errors between *attractor-present* and *attractor-absent* trials on target-mask *overlapping* trials. These trials were intermixed with target-mask *nonoverlapping* trials, which increased the variability in the possible target locations.

Methods

Participants

Participants in all experiments were students from the University of Minnesota between 18 and 33 years old. They had normal color vision and normal or corrected-to-normal visual acuity. Participants were compensated for their time at $10/h or with course credits. Each experiment tested a new group of naive participants.

Eight participants, mean age 20.8 years, completed Experiment 1.

Apparatus

Participants were tested individually in a dimly lit room. They sat 40 cm away from a 19″ CRT computer monitor (resolution: 1280 × 1024 pixels; refresh rate: 75 Hz); a chinrest was used to stabilize viewing distance. The experiment was programmed with Psychtoolbox 3 (Brainard, 1997; Pelli, 1997) implemented in MATLAB.

Stimuli and procedure

Figure 1 (top) illustrates the trial sequence. Each trial started with the presentation of a forward mask centered at fixation. The mask was a red (9.16 cd/m^2) or yellow (25.25 cd/m^2) outline square (4° × 4°, line thickness 0.12°) presented against a black (0.13 cd/m^2) background. The forward mask was presented for 500 ms and followed by the target for localization: a blue (4.57 cd/m^2) outline square centered at fixation. The size of the target was manipulated such that it could appear either inside the

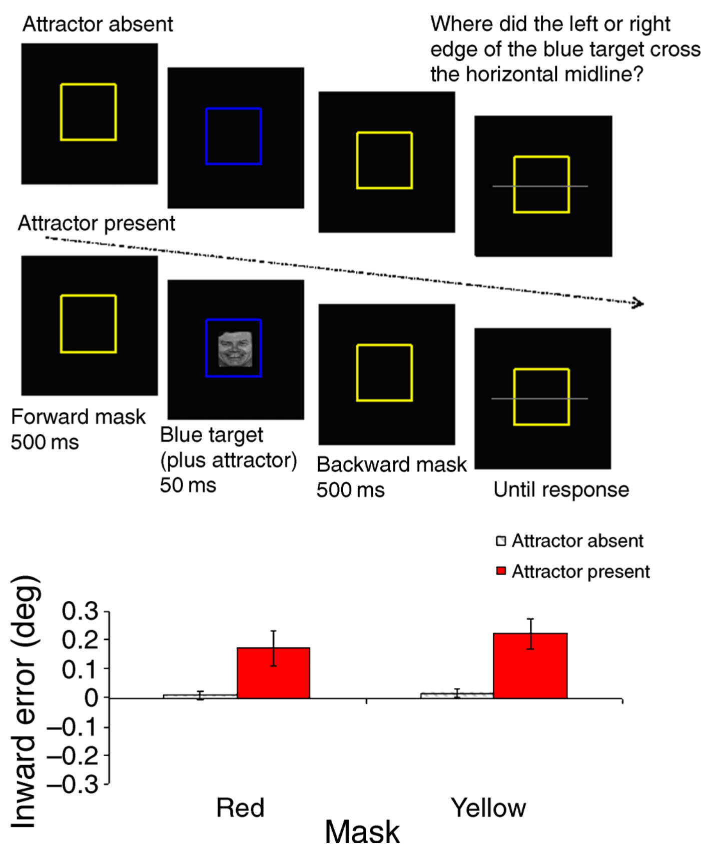

Figure 1. Experiment 1's (top) trial sequence and (bottom) results. Error bars show ±1 *SE* across participants.

mask (2.4° × 2.4° or 3.2° × 3.2°) or outside the mask (4.8° × 4.8° or 5.6° × 5.6°). In the critical overlapping condition, the size of the target was the same as the mask (4° × 4°). The target was presented either by itself or concurrently with a face (the attractor) at the center. The face (2.4° × 2.4°) was randomly selected from a set of four male and four female grayscale faces. The target (and the attractor, when present) was presented for 50 ms and replaced by a backward mask. The backward mask was the same as the forward mask and was presented for 500 ms. Subsequently, a horizontal gray reference line (12° × 0.04°, 6.24 cd/m^2) and a mouse cursor appeared at the center of the display. Participants were asked to click on the position where the left or right edge of the target square crossed the horizontal reference line. No feedback was given and the next trial commenced 500 ms after the response. Demos of the trial sequence from all experiments can be found at http://jianglab.psych.umn.edu/attractor/attractor.htm.

Design

We orthogonally manipulated two factors: *attractor* (present or absent) and *target's position* (overlapping, 4 nonoverlapping). In addition, the mask could be red or yellow. These factors were distributed randomly and evenly across 700 experimental trials.

Analysis

Localization errors were calculated by measuring the horizontal distance between the participants' response and the actual target's left or right edge, whichever was closer to the response. The nonoverlapping trials were included only to increase target-position variability. They rarely produced the phenomenological impression of the VAI. The analyses therefore focus on the target-mask overlapping trials. Data from individual nonoverlapping conditions are presented in Appendix A and generally showed either weak or no VAI.

Results and discussion

Figure 1 (bottom) plots localization errors as a function of the presence of an attractor, separately for red and yellow masks. Participants accurately localized the target's edge when the target was presented in isolation; in these conditions inward error was not reliably different from zero, t's(7) < 1. However, the presence of an attractor led to an inward localization error, $F(1, 7) = 10.26$, $p < 0.015$, $\eta_p^2 = 0.59$ (Cohen's $d = 1.9$), and these results were unaffected by whether the mask was red or yellow, $F(1, 7) < 1$. Thus, the phenomenological impression of perceiving the target as deviating toward the attractor was confirmed. Furthermore, the presence of an attractor also impaired localization precision: The variance of responses was larger for attractor-present trials (*SD*: $M = 0.29$, $SE = 0.03$) than attractor-absent trials (*SD*: $M = 0.16$, $SE = 0.04$), $t(7) = 3.33$, $p < 0.02$. This finding was repeated in all subsequent experiments. However, it is unclear whether the illusion increased response variability, or imprecise signals are more prone to illusory percept.

Could the VAI be attributed to a response bias, where participants were biased toward clicking on a position nearer the attractor whenever it was present? An examination of the target-mask nonoverlapping trials (see Appendix A) suggested that it could not. There was no evidence of a general inward response bias on nonoverlapping trials,[1] suggesting that the localization error observed on overlapping trials was not due to an overall *response* tendency to localize items as closer to the attractor.

Experiment 2: Are faces unique attractors?

Experiment 1 demonstrated that the perceived location of a target that overlaps with a mask deviates toward the location of a concurrently presented, irrelevant face. This effect stood in contrast to the accurate localization of an isolated target. However, upright faces may comprise a unique class of stimuli for the human visual system (e.g., Kanwisher & Yovel, 2006; Moscovitch, Winocur, & Behrmann, 1997), making it necessary to examine whether the VAI occurs for other types of attractors. Therefore, Experiment 2 generalized the illusion to a different type of nonface attractor, a circle.

Methods

Participants

Twelve participants (mean age 20.3 years) took part in Experiment 2.

Stimuli and procedure

This experiment was similar to Experiment 1 except that there were three types of "attractor" trials: the attractor was absent, the attractor was a face (*attractor face*), or the attractor was a gray (1.67 cd/m^2) outline circle (*attractor circle*; circle diameter = 2.4°, line thickness = 0.12°). Each participant was tested on 600 trials, divided into 2 blocks of 300 trials each. Each block included trials that were randomly and evenly divided into three attractor conditions (absent, face, or circle) and five target positions (the target-mask overlapping condition and 4 target-mask nonoverlapping conditions).

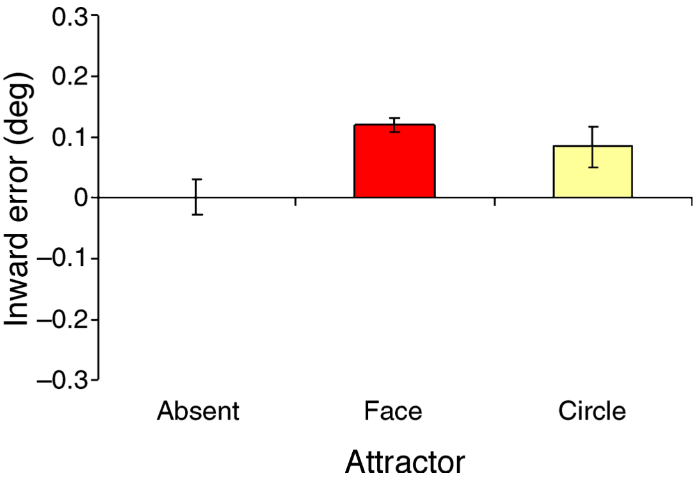

Figure 2. Localization as a function of attractor type, in Experiment 2. Error bars show ±1 *SE* across participants.

The perceived luminance of the blue target square was also equated with the perceived luminance of the red mask using the equiluminant flicker fusion procedure (Bach & Gerling, 1992). The flicker fusion was done prior to the main experiment; the luminance values of the blue targets (2.27 cd/m^2) and red mask (2.69 cd/m^2) were then used in the main experiment.

Results and discussion

Attractor type

Figure 2 shows localization errors from the target-mask overlapping trials, data from the nonoverlapping trials are given in Appendix A. Performance on overlapping trials was significantly influenced by attractor type, $F(2, 22) = 6.79$, $p < 0.01$, $\eta_p^2 = 0.38$. Planned comparisons revealed a significant VAI for faces: inward localization error was greater when the face attractor was present than when there was no attractor, $t(11) = 2.83$, $p < 0.02$, Cohen's $d = 1.08$. This replicated Experiment 1's results with equiluminant stimuli for the target and masks. Importantly, the same pattern was observed for circles, with greater inward localization error when the circle attractor was present than when the attractor was absent, $t(11) = 2.31$, $p < 0.05$, Cohen's $d = 0.88$. However, the VAI was smaller and more variable across participants when the attractor was a circle than a face, $t(11) = 2.35$, $p < 0.04$, perhaps because the circle was perceptually simpler than the faces or because it attracted less attention than faces.

These results were replicated in another unreported study showing that checkerboard attractors also produced a reliable VAI, and that the effect was smaller than the VAI produced by face attractors, $t(10) = 2.12$, $p < 0.061$.

Diminishment of the VAI over time

Because the different types of trials were evenly divided across the first and second halves of the experiment, Experiment 2 enabled us to examine changes in the VAI over time (Table 1). The VAI was present in both halves of the experiment: there was a significant main effect of attractor (absent, face, or circle) in the first half, $F(2, 22) = 6.64$, $p < 0.01$, $\eta_p^2 = 0.38$, and the second half, $F(2, 22) = 4.35$, $p < 0.03$, $\eta_p^2 = 0.28$. In both halves, participants were highly accurate at localizing the target square when the attractor was absent, t's$(11) < 1$. When face or circle attractors were present, they showed an inward error. However, this inward error was smaller in the second half than in the first half of the experiment, $F(1, 11) = 7.51$, $p < 0.02$, $\eta_p^2 = 0.41$.

Although participants showed less inward error on attractor-present trials in the second half of the experiment, this pattern could not be entirely accounted for by a general improvement in localization accuracy. On non-overlapping trials, localization accuracy did not significantly change across the two halves of the experiment (Appendix A), $F(1, 11) < 1$. Therefore the reduced VAI in the overlapping condition appears to reflect an improvement in resisting the attractor illusion. We will come back to this finding when discussing the role of bottom-up and top-down attention in the VAI.

Experiment 3: The role of masking

The first two experiments demonstrated a novel mislocalization illusion. When an irrelevant object was presented concurrently with a target object that was briefly presented and masked, localization of the target

	First half			Second half		
	Attractor absent	Attractor face	Attractor circle	Attractor absent	Attractor face	Attractor circle
Average	0.003	0.156	0.115	−0.001	0.084	0.055
SE	0.014	0.050	0.052	0.001	0.043	0.030

Table 1. Average localization error (deg) as a function of attractor type and experimental half in Experiment 2.

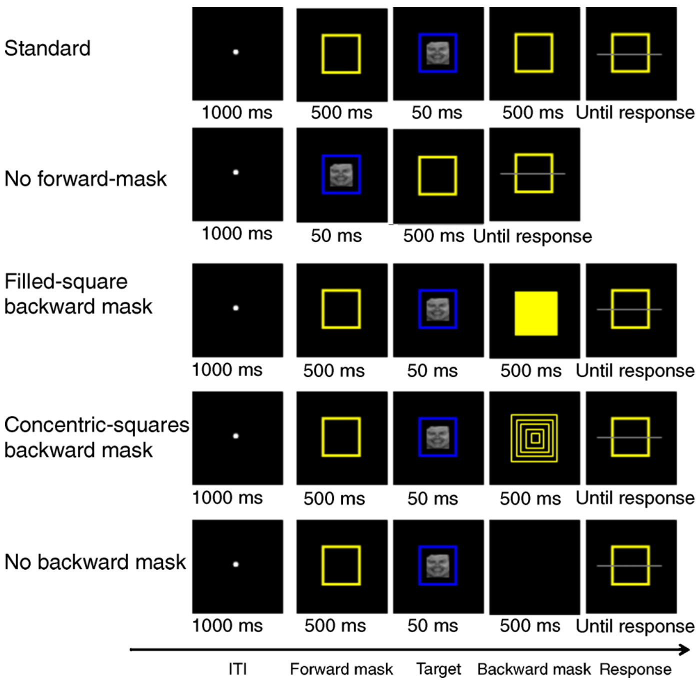

Figure 3. Schematic trial sequence in each of the five masking conditions tested in Experiment 3.

deviated toward the attractor. This illusion occurred across different types of attractors and across different mask colors. However, in both experiments the target was always forward and backward masked. Experiment 3 was designed to directly assess the dependency of the VAI on the presence of forward and backward masks.

Methods

Participants

Ten participants, mean age 19.6 years, completed Experiment 3.

Stimuli and procedure

The general procedure and design was the same as that of Experiment 1 except for the following changes. The intertrial interval (ITI) display increased from 500 ms to 1000 ms and consisted of a white fixation point (50.2 cd/m^2, 0.24° in diameter). We tested five masking conditions (Figure 3): The *standard* condition was the same as that used in Experiment 1 where the target square was preceded by a forward mask and trailed by a backward mask. In the *no forward mask* condition, the 500-ms forward mask display was omitted such that the target was presented immediately after the ITI. In the *no-backward-mask* condition, the 500-ms display following the target was blank. In addition, to investigate the generality of the results we tested two other types of backward mask stimuli. The *filled-square backward mask* condition was similar to the *standard* condition, except that the backward mask involved a filled yellow square (rather than an outline square) centered at fixation (5.2° × 5.2°). The *concentric-squares backward mask* condition was also similar to the *standard* condition, except that the backward mask involved five outline concentric squares (0.4°, 1.6°, 2.8°, 4.0°, 5.2°).

Design

Because of the large number of masking conditions tested, only one inside (3.2° × 3.2°) and one outside (4.8° × 4.8°) target conditions were tested in the nonoverlapping conditions. We orthogonally manipulated three factors: attractor (present or absent), mask condition (*standard, no forward mask, no backward mask, filled-square backward mask,* or *concentric-squares backward mask*), and target's location (overlapping, 2 nonoverlapping).

These factors were distributed randomly and evenly across 720 experimental trials.

Results and discussion

Figure 4 plots localization errors as a function of the presence of the attractor and masking condition in the target-mask overlapping condition. Data from the non-overlapping condition are shown in Appendix A. A repeated-measures ANOVA revealed a main effect of attractor type, $F(1, 9) = 15.57$, $p < 0.01$, $\eta_p^2 = 0.63$. There was also a significant effect of masking condition, $F(4, 36) = 4.43$, $p < 0.01$, $\eta_p^2 = 0.33$, and a significant interaction effect, $F(4, 36) = 3.73$, $p < 0.02$, $\eta_p^2 = 0.29$. Planned comparisons showed larger inward biases in the *attractor-present* trials than in the *attractor-absent* trials in all but the *no-backward-mask* conditions (*standard,* $t(9) = 2.52$, $p < 0.04$; *no forward mask,* $t(9) = 2.23$, $p = 0.053$; *filled-*

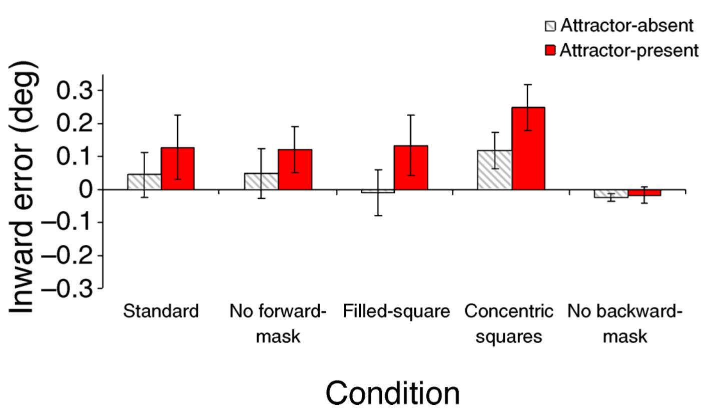

Figure 4. Localization as a function of attractor and masking condition, in Experiment 3. Error bars show ±1 *SE* across participants.

square backward mask, $t(9) = 3.17$, $p < 0.02$; *concentric-squares backward mask,* $t(9) = 4.42$, $p < 0.01$; *no-backward-mask* condition, $t(9) < 1$). Thus, backward masking of the target, but not forward masking of the target, appears to be a necessary condition for the VAI. There was no interaction between the different types of backward masks used (standard, filled-square, concentric-squares) and the attractor effect, $F(2, 18) = 2.51$, $p > 0.25$. This suggests that as long as the target is backward masked it will be mislocalized toward the attractor. The finding that the illusion was not significantly reduced in the *no forward-mask* condition compared to the *standard* condition, $F(1, 9) < 1$, argues against the idea that adaptation to the mask prior to the target's presentation plays a role in the VAI.

Unlike Experiments 1 and 2, the attractor-absent condition (see Appendix A) showed a mislocalization effect, particularly when paired with the concentric-square mask ($t(9) = 2.14$, $p < 0.06$). This finding may reflect a bias in participants' response. That is, because the concentric squares were inside the target and were more salient than the target itself, participants may mistake the mask squares as the target and click on one of the inside squares when making a guess. Notably, even in this condition, mislocalization was significantly greater in the attractor-present than attractor-absent condition, indicating a VAI.

Experiment 3's results clearly suggest that targets need to be briefly presented and masked in order for the VAI to occur. This is in line with the notion that the visual system finds it more difficult to cope with brief events, resulting in more mislocalization effects when targets are presented briefly (Schlag & Schlag-Rey, 2002). Although there is a temporal constraint on the VAI, we think that the temporal constraint is primarily due to the reduced processing duration of the target, which increased location uncertainty. It is unlikely that the VAI results from different processing moments for the target and the attractor due to masking of the target (Bocianski et al., 2008). This is because although only the target was masked in some conditions, in others (e.g., the concentric-square mask or filled-square mask) both the target and the attractor were masked. In these latter conditions, the mask should render both the target and attractor less visible without changing their perceived temporal relationship. Nonetheless, the VAI was observed in those conditions. This finding further distinguishes the VAI from other mislocalization effects that depend on the temporal lag between target and distractors (e.g., Bocianski et al., 2008).

These results also distinguish the VAI from memory mislocalization effects. If the effect of the attractor on target localization operates on mnemonic representations rather than perceptual ones, then the VAI should have been found in all attractor-present conditions, including the *no-backward-mask* condition. Instead, the VAI depends on backward masking, suggesting that the original percept of the target rather than its memory representation was altered. Indeed, the phenomenal impression reported by naive observers is that the "blue square appeared inside the box." Thus, unlike the effects of mislocalization in memory (Sheth & Shimojo, 2001), the visual attractor seems to alter perceptual representations.

Experiment 4: Do the attractors really attract?

Thus far, we have characterized the mislocalization produced by an irrelevant item as an attraction effect. However, this characterization of the mislocalization error may be challenged on several grounds. First, the inward error may reflect a foveal bias (Kerzel, 2002b; Mateeff & Gourevich, 1983) selectively caused by the presence of the attractor. Second, although we have described the illusion as a type of localization error, it may also be interpreted as a type of size illusion. That is, instead of mislocalizing the target square's edges, participants may have perceived the target square as smaller than it really was.

Experiment 4 was designed to dissociate attractor bias from foveal bias and to use a different type of target stimulus that does not confound mislocalization with distortions in perceived size. To this end, we used a modified version of the paradigm in which lines instead of squares were used as targets and masks. The attractor could appear in the left or right visual field or could be absent. If a foveal bias underlies the VAI, then no mislocalization should be found for centrally presented targets (assuming that participants tend to gaze directly at a centrally presented target). Conversely, an attractor bias should lead to mislocalization of the target line toward the attractor (and hence away from the fovea). The use of a line rather than a square as the target also removed any possibility that mislocalization errors reflect a type of size illusion.

Methods

Participants

Twelve participants (mean age 21.5 years) completed Experiment 4.

Stimuli and procedure

This experiment was similar to Experiment 1 except that we simplified the masks and the localization target. Specifically, the forward and backward masks were green lines (37.6 cd/m^2, 4° × 0.12°) and the target was a red (9.16 cd/m^2) or blue (4.57 cd/m^2) line (also 4° × 0.12°). In addition, there were three attractor conditions. The face (4° × 4°) was either absent or presented 3.2° to

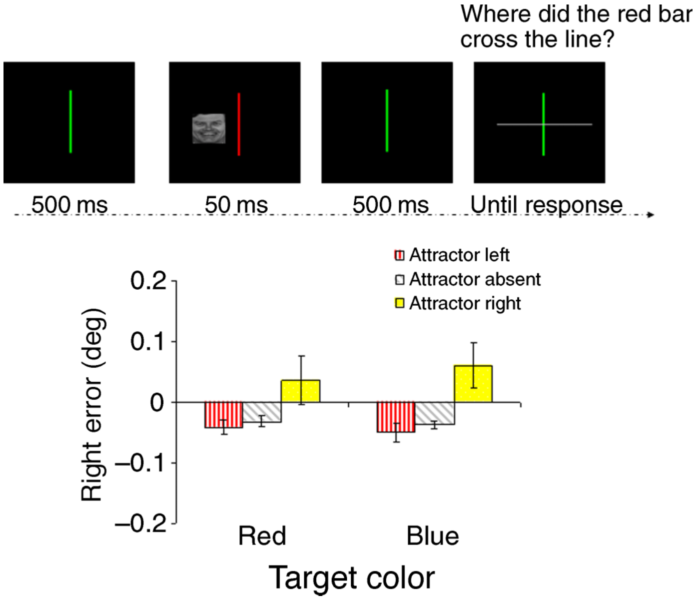

Figure 5. Experiment 4's (top) trial sequence and (bottom) results. Error bars show ±1 *SE* across participants.

the left (*attractor left*) or right (*attractor right*) of fixation (Figure 5, top).

Design

We manipulated the attractor type (*attractor absent, attractor left,* or *attractor right*) and the target's location. The vertical line masks were always presented at the center of the screen. The vertical target line could overlap with the masks (*overlapping*) or could appear 0.4° or 0.8° to the left or right of the masks on *nonoverlapping* trials. Participants were again asked to localize the target line by clicking the mouse cursor on the position that it crossed the horizontal reference line. The cursor appeared together with the reference line, with the cursor at 3.2° above the center of the display. Participants completed 2 blocks, each with 360 trials, divided randomly and evenly into three attractor conditions, five target positions (overlapping, 4 nonoverlapping), and two target colors (red or blue).

The following analysis reported data from the target-mask overlapping trials. The target-mask nonoverlapping trials are presented in Appendix A.

Results and discussion

Figure 5 (bottom) shows localization errors as a function of target position and attractor type, separately for blue and red targets. A repeated-measures ANOVA of attractor condition (absent, left, right) and target color (red, blue) was conducted. An increased tendency to make right errors in attractor-right trials than in both *attractor-left* ($p < 0.04$) and *attractor-absent* trials ($p < 0.07$) resulted in a main effect of attractor, $F(2, 22) = 7.70$, $p < 0.01$, $\eta_p^2 = 0.41$. The numerical trend of larger left errors on *attractor-left* trials than *attractor-absent* trials did not reach significance, $p > 0.24$. The apparent asymmetry between the left and right visual fields requires further investigation. Target color did not influence localization, $F(1, 11) < 1$, and did not interact with attractor condition, $F(2, 22) < 1$.

Similar to Experiment 1, localization was not systematically shifted toward the attractor's position in the nonoverlapping condition (Appendix A), ruling out a general response bias account of the data. These results are the first demonstration that localization of a centrally presented stimulus can be altered by the presence of an irrelevant peripheral object. Moreover, the results distinguish the attractor illusion from foveal bias (Kerzel, 2002b; Mateeff & Gourevich, 1983) because a foveal bias would not have biased the perceived location toward the peripheral attractors. In addition, because the target was a unidimensional object (a line), the mislocalization cannot be attributed to a size illusion.

While we observed a VAI for centrally presented targets, the magnitude of this effect was smaller here than in the previous experiments. A direct comparison between the attractor effect in Experiment 1 (attractor present versus attractor absent) and the attractor effect in Experiment 4 (attractor left versus attractor right) confirmed this observation, $F(1, 18) = 9.77$, $p < 0.01$, $\eta_p^2 = 0.35$. However, the experimental procedures differed in many ways, preventing us from drawing firm conclusions regarding the source of this difference. For instance, it is possible that although foveal bias does not underlie the VAI it contributed to increase the magnitude of the mislocalization in Experiments 1–3 (e.g., Kerzel, 2002b). It is also possible the VAI scales with target eccentricity with smaller mislocalization of targets closer to the center. Conversely, the VAI may scale with attractor eccentricity, with smaller mislocalization of attractors farther in the periphery. Finally, it is also possible that the use of a line reduced the illusion due to its simplicity. These factors need to be examined in future research. Nonetheless, the conclusion remains that a peripheral distractor can bias localization of a centrally presented target.

Experiment 5: The role of onsets

What is the role of attention in producing the VAI? Experiment 2 revealed some indirect evidence that attention might be important in modulating the VAI. First, although the VAI is not restricted to faces, it was stronger when the attractor was a face than when it was a circle (or a checkerboard pattern). This difference may have arisen partly because faces attract more attention due to their social significance or to their greater physical complexity. Second, the magnitude of the VAI diminished over the course of a testing session. In conjunction with the notion that people learn to ignore irrelevant onsets as the experiment progresses (Kelley & Yantis, 2009), these data seem to suggest that the magnitude of the VAI is modulated by attention. The goal of the next two experiments is to explore the processes underlying the attractor illusion by examining whether it is a low-level perceptual effect that does not depend on attention to the attractor, or whether it is a relatively high-level effect that can be modulated by attention.

In Experiment 5 we tested whether the sudden onset of an attractor object is a necessary condition for producing the VAI, or whether the VAI can be revealed by a constant and stable stimulus, analogous to the landmark effect (Sheth & Shimojo, 2001). That is, in all the experiments reported so far the attractor object constituted an abrupt onset, so it may have summoned attention in a bottom-up manner (Yantis & Jonides, 1984). Here, we used the simplified VAI paradigm of Experiment 4 to test the role of sudden onsets in producing the VAI. Specifically, we compared *no-onset* trials where the attractor face was presented throughout a trial with two onset conditions. In the *motion-onset* condition, an attractor face started moving up and down together with the target object's presentation. In the *object-onset* condition, in addition to a constant, static face on one side of the visual field, an additional attractor face was flashed in the opposite visual field.

Methods

Participants

There were 12 participants (mean age 21.3 years) in this experiment.

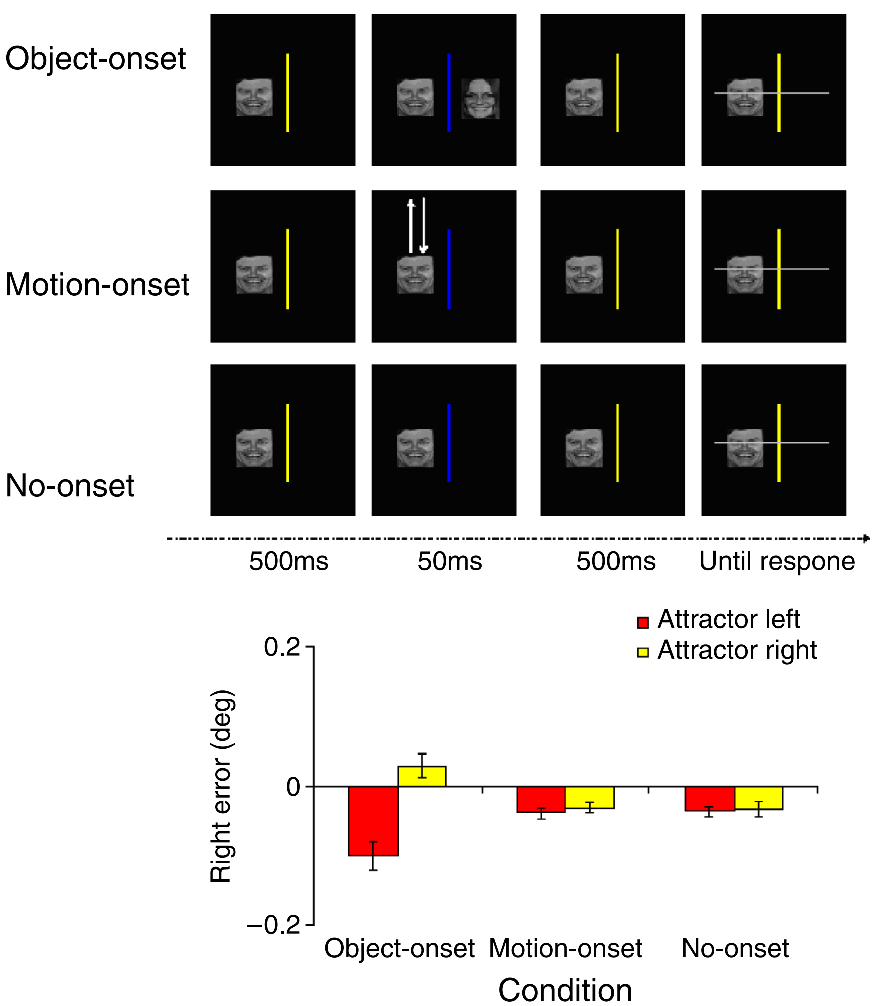

Figure 6. Experiment 5's (top) trial sequence and (bottom) results. Error bars show ±1 *SE* across participants.

Stimuli and procedure

We adopted the line VAI paradigm used in Experiment 4 with the following modifications. On each trial, a mask (vertical yellow line 4° × 0.12°) was presented at the center of the display along with an irrelevant face (4° × 4°) centered at 3.2° to the left or right of fixation. The mask and the irrelevant face were presented for 500 ms, after which a blue target line was presented for 50 ms. The target line could overlap with the mask, or could be 0.4° or 0.8° to the left or right side of the mask line (see Experiment 4).

In the *motion-onset* condition, the original face started moving up and then down at a speed of 25.6°/s concurrently with the target line's presentation. In the *object-onset* condition, an additional face was presented at the opposite side of the original face, and its presentation coincided with the target line's presentation. In the *no-onset* condition, the original face did not move, neither was a new face added (Figure 6, top). Other aspects of the experiment were the same as in Experiment 4.

Participants completed 2 blocks of 360 trials each, divided randomly and evenly into 5 target positions (overlapping, 4 nonoverlapping) and three attractor onset conditions (no onset, motion onset, or object onset). The original face was equally likely to be on the left or right side of fixation.

Results and discussion

Figure 6 (bottom) shows localization errors as a function of the attractor's position and onset condition. First, when the attractor face was a constant, static object presented 500 ms before the target line, we observed no VAI. Localization was independent of whether the original face was presented on the left or right side of the screen, $t < 1$. Second, the VAI was also absent when the attractor object started moving (*motion onset*), $t < 1$. Finally, a significant VAI was observed when a new attractor face flashed on the opposite side of the original static face. In this case, the VAI was revealed as a bias toward the flashed attractor, $t(11) = 4.29$, $p < 0.01$. An ANOVA on the attractor's side and attractor onset condition revealed a significant interaction effect, $F(2, 22) = 15.07$, $p < 0.01$, $\eta_p^2 = 0.58$.

These results show that the VAI was induced only when the attractor was presented as a sudden object onset. In contrast, a constant, static attractor object did not induce the VAI, further distinguishing the VAI from the landmark effect (Sheth & Shimojo, 2001). On the other hand, motion onset, which may also automatically capture attention (Abrams & Christ, 2003), was ineffective in inducing a VAI. The ineffectiveness of motion onset in this experiment may be driven in part by the nature of the target object. Because the target object was presented as an abrupt onset, it may have promoted an attentional set of looking for object onsets. This attentional set would increase the likelihood that the abrupt onset of an attractor, but not necessarily the onset of motion, would capture attention (Folk, Remington, & Wright, 1994).

Experiment 6: Task-relevant attractors

Low-level effects underlie many perceptual illusions. For example, the Müller–Lyer illusion can be revealed even when participants are not attending to the illusion inducers (Moore & Egeth, 1997), suggesting that contextual information influences low-level processes. Indeed, Experiment 5 showed that bottom-up attention plays an important part in inducing the VAI. However it is not clear whether top-down attention is capable of modulating the illusion. To test the effect of top-down attention on the VAI, the final experiment compared the VAI when the attractor was task-relevant and task-irrelevant.

Methods

Participants

There were eleven participants (mean age 24.1 years) in this experiment.

Stimuli and procedure

The general procedure and stimuli were the same as those of the standard paradigm used in Experiment 1. To evaluate the role of attention, we tested participants in two types of blocks. In the *attractor-relevant* blocks, participants were asked to report, after making the localization response, whether there was a male, a female, or no face on that trial. They entered their response by pressing one of three number keys (1–3). Feedback in the form of a green plus or a red minus sign was provided for the gender discrimination response for 300 ms. In the *attractor-irrelevant* blocks, participants made no response to the faces. There were a total of 12 blocks presented in an ABAB…AB order, counterbalanced across subjects. Each block consisted of 50 trials divided randomly and evenly into five target positions (overlapping, 4 nonoverlapping) and two attractor conditions (present or absent), for a total of 600 trials.

Results and discussion

Face judgment accuracy

In the *attractor-relevant* blocks, participants rarely pressed the "male" or "female" keys when the face was absent (M = 1.8%, SD = 1.3%). When the face was present, the error rate was 11.5% (SD = 4.8%). In the following analysis, we removed trials in which the face judgment was incorrect, although the same pattern of results was observed when all trials were included.

Localization accuracy

Figure 7 shows localization errors as a function of the presence of the attractor separately for attractor-irrelevant and attractor-relevant blocks. A repeated-measures ANOVA revealed a main effect of attractor, $F(1, 10) = 21.22$, $p < 0.01$, $\eta_p^2 = 0.68$, as a larger inward bias was found on attractor-present than on attractor-absent trials. The main effect of the attractor's task relevance was not significant, $F < 1$, but the interaction between attractor's presence and its task relevance was significant, $F(1, 10) = 6.47$, $p < 0.03$, $\eta_p^2 = 0.39$. Specifically, the attractor illusion was observed both when the attractor was task-relevant, $t(10) = 4.48$, $p < 0.01$, and when it was task-irrelevant, $t(10) = 4.13$, $p < 0.01$, but it was significantly greater in the former.

The lack of a main effect of block type in the overlapping and nonoverlapping trials (Appendix A) suggests that increasing task load in the attractor-relevant blocks did not generally impair localization. Instead, task-relevant attractors had a selective effect of increasing the VAI. The finding that amplified attention to the attractor increased the magnitude of the VAI is consistent with the idea that the VAI is a relatively high-level effect modulated by attention.

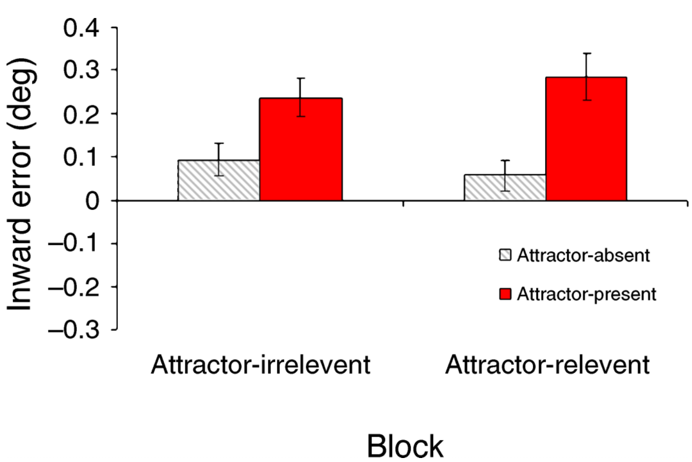

Figure 7. Localization as a function of attractor's presence and relevance, in Experiment 6. Error bars show ±1 *SE* across participants.

General discussion

This study reports a visual illusion called the visual attractor illusion (VAI). It refers to the mislocalization of a briefly presented and masked object (e.g., an outline square or a line) when presented concurrently with a neighboring object. The illusion was found across different attractor types and across different colors of targets and masks. The illusion does not require the presence of a forward mask. However, the presence of a backward mask that overlaps with the target object appears to be a necessary condition for inducing the VAI. In addition, the VAI is abolished when the attractor is not a new object onset, is stronger when the attractor object is task-relevant rather than irrelevant, and diminishes as the experiment progresses. These findings suggest that VAI is a relatively high-level effect modulated by attention.

The VAI is a relatively unique phenomenon and it can be distinguished from other mislocalization effects. For instance, unlike the foveal bias, the VAI requires the presence of a neighboring stimulus for the mislocalization to occur and more importantly the localization bias is toward the attractor rather than simply toward the fovea. The VAI is also not a size illusion as it is observed for unidimensional targets (e.g., lines) as well as for two-dimensional targets (e.g., squares). The VAI can further be distinguished from the landmark effect, in which spatial memory is shifted toward the position of a salient, stable stimulus (Sheth & Shimojo, 2001) because it is eliminated when the attractor object is a constant, static object. In addition, the prerequisite of backward masking and the phenomenal impression of seeing the object as closer to the attractor than it actually is argue against the VAI as a memory effect.

Unlike other mislocalization effects that involve moving stimuli (Jancke & Erlhagen, in press; Müsseler, Stork, & Kerzel, 2002), the VAI does not involve motion. It has been claimed that sampling spatial signals across short periods of time underlies the mislocalization of moving items (Eagleman, 2001). It has also been suggested that mislocalization effects of stationary objects involve the integration of signals over time (Bocianski et al., 2008). Thus, given the transient nature of the VAI (i.e., its reliance on brief presentation and on backward masking), it is possible that a similar mechanism of averaging positional signals over a short time window might be involved here as well. It remains to be seen whether time, and more specifically the accumulation of information over time, is a critical factor in the VAI, or whether briefly presented and masked stimuli are needed simply to uncover localization processes that are otherwise concealed by prolonged viewing (Schlag & Schlag-Rey, 2002).

Attention, both top-down and bottom-up (Egeth & Yantis, 1997), plays a prominent role in the VAI. Top-down attentional effects are revealed as the VAI is increased when the attractor object is task-relevant rather than irrelevant. Bottom-up attentional effects are revealed because the VAI depends on the transient, abrupt onset of the attractor object. The underlying mechanism of the VAI may, to some extent, be analogous to that of other position distortions induced by motion (Watanabe & Yokoi, 2006) or saccade planning (Ross, Morrone, & Burr, 1997). Saccade planning may dynamically reshape the receptive field of neurons, leading to the compression of space around the saccade target (Ross et al., 1997). Similarly, an analogous compression of perceptual space may be caused by a transient capture of attention by a salient object. Indeed, visuospatial shifts in attention activate similar neural networks as those activated by saccade planning (Awh, Armstrong, & Moore, 2006). Thus, it is possible that transient attention compresses perceptual space, much like saccade planning (Ross et al., 1997), such that nearby objects are perceived as closer to the attractor. According to this account, one might expect the VAI to be stronger when the attractor is presented before the target. However, as we discuss below, desynchronizing the presentation might reduce the grouping strength of the two, reducing or eliminating the VAI. Further examination of the role of visuospatial attention in the VAI may therefore be critical to understanding its origins.

Alternatively, it is possible that when the location of one briefly presented object is uncertain (e.g., when it is masked), its position is weighted toward the location of a second, concurrently presented object. In line with this idea, Greenwood, Bex, and Dakin (2009) have recently reported that visual crowding is partly explained by positional averaging between the target object and the flankers. However, unlike crowding effects where the targets appear in the periphery (15° eccentricity in Greenwood et al., 2009), the VAI targets appear at the center of the screen, a condition that usually does not induce crowding (Pelli, Palomares, & Majaj, 2004). The notion of positional averaging is also in agreement with models of edge detection that assume that edges are detected and localized mainly by a luminance analysis of the local environment (e.g., Georgeson, May, Freeman, & Hesse, 2007; Morrone & Burr, 1988). Accordingly, presenting a target close to a salient stimulus (e.g., a briefly presented face) changes the luminance profile of the target's local surroundings, potentially shifting the outcome of the edge analysis closer to the attractor.

More generally, the VAI may be an example of a "grouping and assimilation" effect. The target object is grouped with the attractor perhaps by virtue of their common onset and becomes assimilated with the attractor. The idea that the mislocalization seen in the current study may reflect a more general grouping-and-assimilation effect is supported by observations in the motion-onset condition of Experiment 5. In that condition, the attractor was a moving stimulus. Although it did not change the target's perceived location, it led to the subjective impression that the target moved in the same direction as the moving attractor. Future research that manipulates the grouping strength between the attractor and the target is needed to test this hypothesis.

Whether the VAI reflects a warping of perceptual space by transient attention to the attractor or position averaging of nearby objects requires further research. We also do not yet know the specific temporal characteristics of the VAI. For instance, it is unclear whether the target and attractor objects must occur simultaneously (which strengthens grouping), or whether the VAI can be observed when the two stimuli are temporally desynchronized. Additionally, although the brief presentation of targets and distractors argues against the involvement of eye movements in the illusion, a systematic investigation is required to establish the relationship between gaze fixation, eccentricity, and the VAI. Future research that tracks participants' eye gaze position is needed to address these issues.

The important role of attention in producing the VAI extends previous findings showing that the focus of attention modulates spatial representations (Baldo & Klein, 1995; Kerzel, 2002a; Olivers, 2004; Shim & Cavanagh, 2005; Suzuki & Cavanagh, 1997; Tsal & Bareket, 2005; Uddin, Kawabe, & Nakamizo, 2005; Yamada, Kawbe, & Miura, 2008). Previous studies have shown that spatial attention improves fine-grained localization (Tsal & Bareket, 2005). Moreover, focusing attention on a specific location prior to a target's appearance sometimes causes the target to be displaced away from the focus of attention (Suzuki & Cavanagh, 1997) and sometimes closer to the focus of attention (Yamada et al., 2008). However, although the VAI is also modulated by attention, caution should be taken in comparing the phenomenon reported here to these previous observations for two reasons. First, in the VAI paradigm spatial attention is not directly manipulated before the target's appearance, making it difficult to draw conclusions about the role of spatial attention in this particular mislocalization illusion. Second, these experiments explored how the concurrent presence of a neighboring stimulus affects localization of a target. In this respect, the VAI resembles the landmark effect, which is revealed when spatial memory is shifted toward an irrelevant object (Kerzel, 2002a; Sheth & Shimojo, 2001).

In sum, this study presents a visual illusion in which the perceived location of an object is drawn toward the location of a concurrently presented object. The precise mechanism of the VAI remains to be determined, although transient attention to the attractor object appears to play an important role in modulating this illusion.

Appendix A

Table A1 and Figure A1.

	Inside two steps		Inside one step		Outside one step		Outside two steps	
	Attractor absent	Attractor present	Attractor absent	Attractor present	Attractor absent	Attractor present	Attractor absent	Attractor present
Experiment 1	−0.014 (0.026)	0.02 (0.024)	0.087 (0.021)	0.125 (0.020)	−0.028 (0.038)	−0.062 (0.037)	−0.048 (0.043)	−0.072 (0.063)
	$p = 0.07$		$p = 0.10$		$p = 0.13$		$p = 0.38$	
Experiment 2: Face	0.011 (0.037)	0.018 (0.045)	0.034 (0.026)	0.075 (0.029)	0.019 (0.022)	0.009 (0.036)	0.090 (0.049)	0.087 (0.062)
	$p = 0.72$		$p < 0.01$		$p = 0.57$		$p = 0.86$	
Experiment 2: Circle		0.047 (0.047)		0.076 (0.029)		0.014 (0.030)		0.093 (0.047)
	$p < 0.05$		$p < 0.01$		$p = 0.69$		$p = 0.87$	

	Inside two steps		Inside one step		Outside one step		Outside two steps	
Experiment 2	First half	Second half	First half	Second half	First half	Second half	First half	Second half
Attractor absent	0.029 (0.036)	−0.008 (0.043)	0.035 (0.026)	0.034 (0.028)	0.006 (0.022)	0.032 (0.023)	0.062 (0.056)	0.119 (0.044)
Attractor face	0.037 (0.047)	−0.001 (0.047)	0.089 (0.030)	0.062 (0.029)	0.009 (0.041)	0.009 (0.033)	0.061 (0.077)	0.114 (0.049)
Attractor circle	0.089 (0.050)	0.006 (0.046)	0.093 (0.029)	0.060 (0.030)	−0.001 (0.041)	0.029 (0.023)	0.072 (0.055)	0.043 (0.062)

	Inside two steps		Inside one step		Outside one step		Outside two steps	
	Attractor absent	Attractor present	Attractor absent	Attractor present	Attractor absent	Attractor present	Attractor absent	Attractor present
Experiment 3: Standard			0.030 (0.029)	0.042 (0.026)	−0.046 (0.019)	−0.053 (0.028)		
			$p = 0.5$		$p = 0.57$			
Experiment 3: No forward			0.039 (0.033)	0.070 (0.029)	−0.034 (0.023)	−0.048 (0.035)		
			$p = 0.10$		$p = 0.36$			
Experiment 3: Filled square			0.050 (0.028)	0.007 (0.031)	0.078 (0.045)	0.075 (0.029)		
			$(-)p < 0.02$		$p = 0.91$			
Experiment 3: Concentric squares			0.182 (0.074)	0.184 (0.066)	0.102 (0.059)	0.183 (0.064)		
			$p = 0.94$		$p < 0.05$			
Experiment 3: No backward			0.029 (0.025)	0.097 (0.036)	−0.036 (0.033)	−0.052 (0.039)		
			$p < 0.02$		$p = 0.47$			

	Left two steps		Left one step		Right one step		Right two steps	
	Attractor left	Attractor right	Attractor left	Attractor right	Attractor left	Attractor right	Attractor left	Attractor right
Experiment 4	0.172 (0.048)	0.136 (0.053)	−0.042 (0.032)	−0.017 (0.032)	−0.025 (0.031)	−0.013 (0.033)	−0.166 (0.050)	−0.184 (0.049)
	$p = 0.27$		$p = 0.36$		$p = 0.29$		$p = 0.36$	
Experiment 5: Object onset	0.056 (0.041)	0.073 (0.038)	−0.066 (0.028)	0.010 (0.014)	−0.079 (0.142)	−0.020 (0.020)	−0.173 (0.030)	−0.103 (0.034)
	$p = 0.67$		$p < 0.01$		$p < 0.01$		$p = 0.08$	
Experiment 5: Motion onset	0.075 (0.034)	0.093 (0.027)	−0.002 (0.014)	−0.002 (0.015)	−0.059 (0.013)	−0.057 (0.016)	−0.189 (0.028)	−0.136 (0.018)
	$p = 0.59$		$p = 0.95$		$p = 0.86$		$p = 0.02$	
Experiment 5: No onset	0.063 (0.031)	0.136 (0.110)	−0.004 (0.017)	−0.007 (0.018)	−0.061 (0.015)	−0.066 (0.014)	−0.160 (0.029)	−0.153 (0.026)
	$p = 0.08$		$p = 0.72$		$p = 0.47$		$p = 0.81$	

	Inside two steps		Inside one step		Outside one step		Outside two steps	
	Attractor absent	Attractor present	Attractor absent	Attractor present	Attractor absent	Attractor present	Attractor absent	Attractor present
Experiment 6: Irrelevant	−0.010 (0.051)	−0.123 (0.057)	0.020 (0.031)	0.049 (0.034)	−0.015 (0.031)	−0.028 (0.059)	−0.160 (0.076)	−0.117 (0.102)
	$(-)p < 0.01$		$p = 0.14$		$p = 0.33$		$p = 0.47$	
Experiment 6: Relevant	−0.050 (0.051)	−0.161 (0.056)	−0.015 (0.035)	0.021 (0.032)	0.005 (0.043)	0.118 (0.086)	−0.127 (0.096)	−0.030 (0.119)
	$(-)p < 0.01$		$p = 0.09$		$p = 0.18$		$p = 0.26$	

Table A1. Average inward localization errors of nonoverlapping targets as a function of the presence of an attractor in all experiments. Standard errors of the mean are presented in parentheses and the *p*-values of two-tailed, paired-samples *t*-tests comparing attractor-present and attractor-absent trials are presented at the bottom. The minus sign before the *p*-value indicates an effect opposite to the VAI.

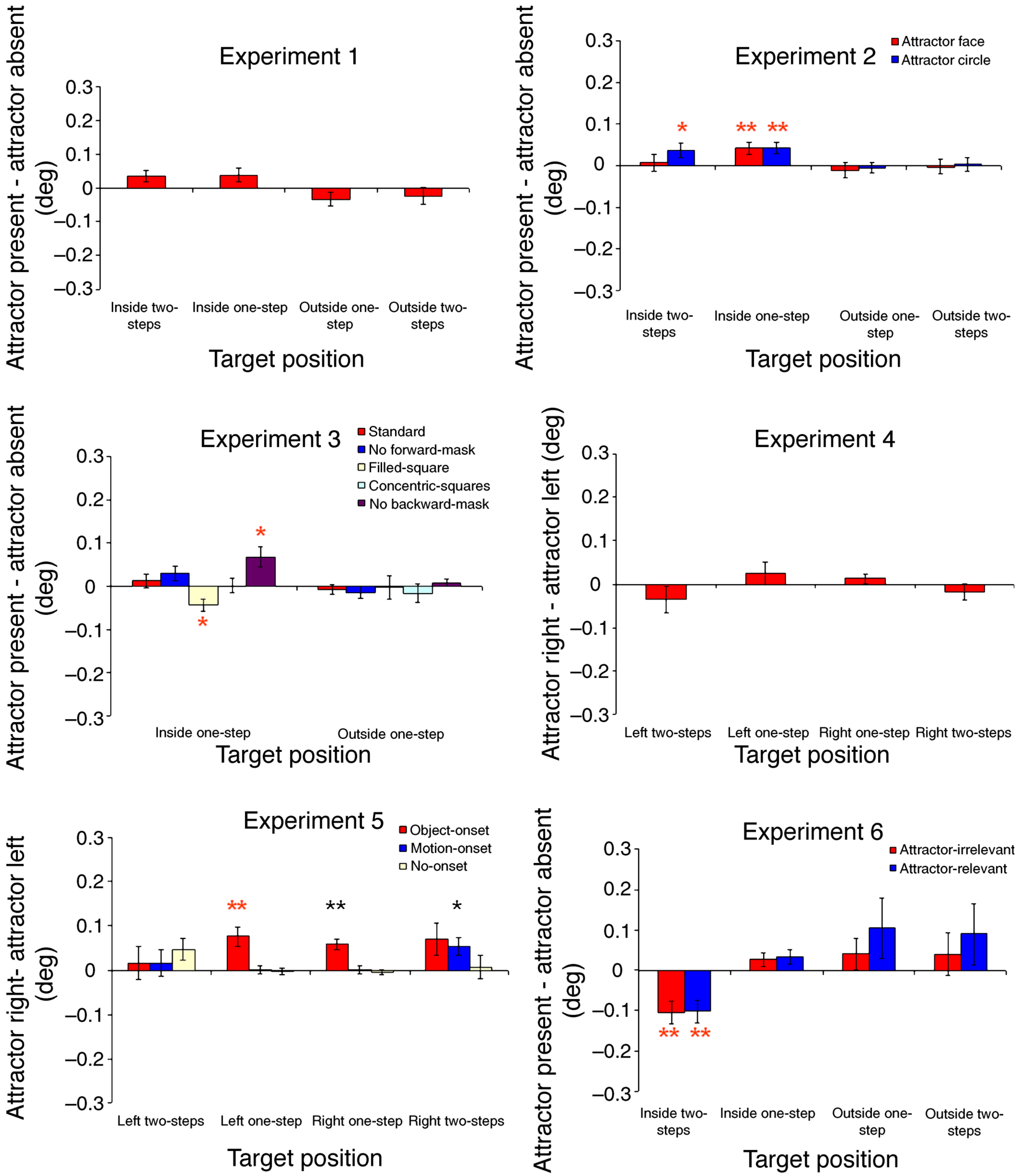

Figure A1. The attractor effect as measured by the difference in localization errors between attractor-present and attractor-absent trials (or attractor-right minus attractor-left trials in Experiments 4 and 5) in each of the nonoverlapping positions across all experimental conditions. Error bars show ±1 *SE* across participants and red asterisks indicate reliable difference from zero (**p* < 0.05, ** *p* < 0.01).

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Footnote

[1]There was a tendency of an inward bias for inside targets and an outward bias for outside targets in some experiments. However, when present, attractor effects in the nonoverlapping conditions were much smaller than in the overlapping condition. These effects were also not consistent (Experiment 6 showed the reverse pattern) or reliable across experiments.

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