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Perceptual organization, visual attention, and objecthood

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ABSTRACT

We have previously demonstrated that the mere organization of some elements in the visual field into an object attracts attention automatically. Here, we explored three different aspects of this automatic attentional capture: (a) Does the attentional capture by an object involve a spatial component? (b) Which Gestalt organization factors suffice for an object to capture attention? (c) Does the strength of organization affect the object's ability to capture attention? Participants viewed multi-elements displays and either identified the color of one element or responded to a Vernier target. On some trials, a subset of the elements grouped by Gestalt factors into an object that was irrelevant to the task and not predictive of the target. An object effect – faster performance for targets within the object than for targets outside the object – was found even when the target appeared after the object offset, and was sensitive to target–object distance, suggesting that the capture of attention by an object is accompanied by a deployment of attention to the object location. Object effects of similar magnitude were found for objects grouped by a combination of factors (collinearity, closure, and symmetry, or closure and symmetry) or by a single factor when it was collinearity, but not symmetry, suggesting that collinearity, or closure combined with symmetry, suffices for automatic capture of attention by an object, but symmetry does not. Finally, the strength of grouping in modal completion, manipulated by varying contrast polarity between and within elements, affected the effectiveness of the attentional capture by the induced object.

1. Introduction

Perceptual organization and visual attention are crucial for the perception of our visual environment and to visuomotor behavior. Perceptual organization refers to the processes by which the disjoint bits of visual information are structured into the larger coherent units that we eventually experience as environmental objects. The Gestalt psychologists, who were the first to study perceptual organization, suggested that organization is composed of grouping and segregation processes (Koffka, 1935; Köhler, 1938; Wertheimer, 1938), and identified several stimulus factors that determine organization. These include grouping factors such as proximity, good continuation, similarity, common fate, and closure (Wertheimer, 1938), and factors that govern figure-ground organization, such as surroundedness, relative size, contrast, convexity, and symmetry (Rubin, 1958). Modern researchers have identified additional factors: Common region (Palmer, 1992) and element connectedness (Palmer & Rock, 1994), which support grouping, and familiarity (Peterson & Gibson, 1994), lower region (Vecera, Vogel, & Woodman, 2002), spatial frequency (Klymenko & Weisstein, 1986), top–bottom polarity (Hulleman & Humphreys, 2004a), and extremal edges (Palmer & Ghose, 2008), which support figure-ground assignment. Psychophysical research have provided quantitative measures for many of the classical and new factors and documented their role in perceptual organization and object perception (e.g., Elder & Zucker, 1993, 1994; Feldman, 2001; Kellman & Shipley, 1991; Kimchi, 2000; Kubovy & Wagemans, 1995; for recent reviews see, Peterson & Kimchi, 2013; Wagemans et al., 2012).

Visual attention refers to the processes by which some visual information in a scene is selected, in particular, information that is most relevant to ongoing behavior. Deployment of attention can be goal-directed, based on deliberate behavioral goals of the observer (e.g., Desimone & Duncan, 1995; Egeth & Yantis, 1997; Posner, 1980). Deployment of attention can also be stimulus-driven. In this case, attention is captured involuntarily by certain stimulus events, such as a salient singleton (e.g., Theeuwes, De Vries, & Godjin, 2003), or an abrupt onset of a new perceptual object and some other types of simple luminance and motion transients (e.g., Abrams & Christ, 2003; Franconeri, Simons, & Junge, 2004; Jonides, 1981; Yantis & Hillstrom, 1994).

The relationship between perceptual organization and visual attention is multifaceted and mutually constrained

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(e.g., Driver, Davis, Russell, Turatto, & Freeman, 2001; Scholl, 2001; van Leeuwen et al., 2011; for recent reviews see, Gillebert & Humphreys, 2015; Kimchi, 2009). Findings such as greater disruptive effect of response-incompatible distractors on target discrimination when the target and distractors are strongly grouped by Gestalt factors (e.g., Kramer & Jacobson, 1991), easier responding to two features when they belong to the same object than when they belong to two separate objects (e.g., Duncan, 1984), and the smaller cost associated with target detection when attention is initially cued to a non-target location for targets that appear in the same object as the cue than for targets appearing in a different object (e.g., Egly, Driver, & Rafal, 1994), demonstrate that perceptual organization constrains attentional selection. Further evidence comes from studies with patients with attention deficits, showing for example, a recovery from extinction as a result of grouping contralesional items with ipsilesional items on the basis of Gestalt factors (e.g., Mattingley, David, & Driver, 1997), and from fMRI and ERPs studies that found that attended and unattended stimuli belonging to the same object elicited a very similar response pattern in the visual cortex (e.g., Martinez, Teder-Salejarvi, & Hillyard, 2007; Martinez et al., 2006).

Attention can also constrain perceptual organization (e.g., Freeman, Sagi, & Driver, 2001, 2004; Han, Jiang, Mao, Humphreys, & Gu, 2005; Han, Jiang, Mao, Humphreys, & Qin, 2005; Peterson & Gibson, 1994; Vecera, Flevaris, & Filapek, 2004). For example, Freeman et al. (2001) showed that detection of a central Gabor target was improved by flankers collinear with the target only when the flankers were attended to; when unattended these flankers did not interact with the target, as if they were not physically present in the display. Vecera et al. (2004) showed that when spatial attention is directed to one of the regions of an ambiguous figure-ground stimulus, the attended region is perceived as figure and the shared contour is assigned to the attended region. Whether perceptual organization can be accomplished without attention appears to depend on the type of perceptual organization and on the processes involved. For example, Kimchi and Razpurker-Apfeld (2004) showed that grouping elements into columns/rows by color similarity (see also, Russell & Driver, 2005; Shomstein, Kimchi, Hammer, & Behrmann, 2010) can take place without attention, whereas grouping elements into a shape by color similarity cannot, and figure-ground segmentation can occur under inattention when the cue is convexity (Kimchi & Peterson, 2008), but not when the cue is symmetry (Rashal, Kimchi & Yeshurun, in preparation).

The critical role of perceptual organization in structuring the visual information and designating potential objects raises another important issue concerning the interplay between perceptual organization and attention: Can perceptual organization affect the automatic, stimulus-driven deployment of attention? Assuming that the Gestalt organization factors and perhaps other non-accidental properties are likely to reflect environmental regularities, probabilistically implying objects in the environment (e.g., Driver et al., 2001), granting priority to a perceptual unit that conforms to Gestalt factors is a desirable characteristic for a system whose goal is to construct a meaningful representation of the environment, identify and recognize objects and act upon them.

Following this reasoning, Kimchi and colleagues (Kimchi, Yeshurun, & Cohen-Savransky, 2007; Yeshurun, Kimchi, Sha'shoua, & Carmel, 2009) examined whether the mere organization of some elements in the visual field into an object captures attention automatically, in a stimulus-driven manner.[1] Several previous studies, demonstrating object-based attentional effects, showed that attention can be deployed to an object (e.g., Egly et al., 1994; Kramer & Jacobson, 1991), but none of these studies showed unequivocally that the object per se was the factor that attracted attention, because there were always other factors that directed attention to a part or an attribute of the object, such as cuing or instructions.

In the study of Kimchi et al. (2007), observers were presented with an array of multiple *L* elements, a subset of which formed an object (a diamond-like configuration) on some trials (object trials) and no object on the other trials (No-object trials). The task was to report the color of a target, which was defined by its location relative to an asterisk (e.g., above or right to the asterisk). The asterisk appeared 150 ms following the onset of the elements array, and in the object trials, it could appear inside the object (Inside-object trials) or outside the object (Outside-object trials). The object was task irrelevant, not predictive of the target, and was not associated with unique abrupt onset or any other unique transient. Nonetheless, response times to the target on the object trials were faster when the asterisk appeared within the object and slower when the asterisk appeared outside the object; also, response times were faster in the Inside-object trials than in the No-object trials (benefit) and slower in the Outside-object trials than in the No-object trials (cost). These findings indicate that the object captured attention automatically, in a stimulus-driven manner.

In a further experiment (Yeshurun et al., 2009) we replicated the object effect when the target was not a part of the object and with simplified task demands. As in our previous study, observers were presented with an array of *L* elements, some of which formed an object on some trials. The target was a Vernier stimulus comprised of two vertical lines, one line appearing above the other and separated by a small horizontal offset, and the observers had to indicate the direction of the offset (left or right). Performance was faster and more accurate when the target appeared in the center of the object than in a non-object location, and this effect was observed even when the target appeared after the elements array disappeared, indicating automatic deployment of attention to the object, and suggesting the involvement of a spatial component.

Thus, our previous results (Kimchi et al., 2007; Yeshurun et al., 2009) demonstrate unequivocally that a perceptual object, in itself, can capture attention automatically. The current work addresses three core issues concerning this unique, perceptual organization-driven attentional capture.

(1) Does the attentional capture by a perceptual object involve a spatial component? Previous research has suggested that attentional selection can occur on the basis of spatial and object representations simultaneously (e.g., Egly et al., 1994; Kravitz & Behrmann, 2008; Vecera & Farah, 1994), and our pervious study (Yeshurun et al., 2009) suggested the involvement of a spatial component in the automatic deployment of attention to the object. The first study (Experiments 1a and 1b) is concerned with a further examination of this issue by investigating not only the presence of object effects after the disappearance of the object, but also the sensitivity of the object effect to spatial manipulations. To this end we used an array with a larger number of elements than in our previous studies and tested object effects and the effect of the distance between the target and the object on performance, both when the target and the object were present in the display simultaneously and when the target appeared after the object disappeared. To foreshadow, the results provided further converging evidence that a perceptual object captures attention automatically and that this

[1] What constitutes an object in visual perception has turned out to be a rather difficult question to answer (e.g., Feldman, 2003; Scholl, 2001). In our work we refer to an object as 'elements in the visual scene organized by Gestalt factors into a coherent unit'.

attentional capture involves a deployment of attention to the spatial locations occupied by the object.

(2) Which Gestalt organization factors suffice for an object to capture attention? The second study (Experiments 2a–2d) is concerned with this important question, the answer to which may provide insights into the nature of the early formation of "objecthood". The objects that were present in the arrays in our previous studies (including the present Experiments 1a and 1b) were grouped by the combination of the Gestalt factors of good continuation (henceforth collinearity), closure, and symmetry. Previous findings demonstrated the contribution of collinearity and closure to perceptual organization, whereas the contribution of symmetry has been less clear (e.g., Wagemans et al., 2012). In this study we examined the role of these factors in the capture of attention by a perceptual object. We compared the attentional capture by an object that is grouped by a single factor (collinearity or symmetry), and attentional capture by an object grouped by a combination of two factors (closure and symmetry), to the attentional capture by an object that is grouped by all three factors combined. To foreshadow the results, collinearity alone sufficed for an object to capture of attention, and so did closure combined with symmetry, but symmetry alone did not.

(3) Does the strength of perceptual organization affect the ability of the object to capture attention? If attention is captured by a perceptual object – an organized coherent unit, then the strength of organization is expected to have an effect on this attentional capturer. The third study (Experiments 3a–3d) was designed to address this issue. We extended our investigation to illusory objects, and examined whether the strength of perceptual grouping involved in modal completion, manipulated by reversals in contrast polarity between and within inducers (e.g., Spehar, 2000), affects the ability of the object to capture attention. To foreshadow the results, the illusory object captured attention automatically, much like a real object, and this capture of attention depended on the strength of the illusory contours: when illusory contours were strong, so was the ability of the illusory object to capture attention, when the illusory contours were weak, the ability to capture attention was weakened.

In all the experiments reported in this article, observers were presented with an array of elements, a subset of which were organized by some Gestalt factors into a coherent unit – an object – on some of the trials. The task varied between experiments and included discriminating the offset direction of a Vernier target, or identifying the color of a target element. The target could appear within the object or in a non-object location in the display. As in our previous studies, the object was task-irrelevant and non-predictive of the target, so that there was no incentive for the observers to deliberately attend the object, nor was there any factor known to capture attention, such as a singleton, an abrupt onset, or any other unique transient, associated with the object. If attention is automatically deployed to the object then performance is expected to be best when the target appears within the object and worst when the target appears in a non-object location.

2. Study 1: Experiments 1a–1b

The aim of these experiments was twofold: to provide converging evidence that attention is deployed automatically to a perceptual object, and to further investigate the involvement of a spatial component in this automatic deployment of attention. To this end we presented observers with a larger display that included 6×6 elements (in comparison to the 9-element display in Kimchi et al., 2007, and the 16-element display in Yeshurun et al., 2009) in various orientations. The target was a Vernier stimulus. A subset of the elements formed an object (a square) on some of the trials, and the target could appear in the center of the object (Inside-object condition) or in a non-object location (Outside-object condition). The larger 36-element display allowed us to test the effect of the distance between the target and the object (in the Outside-object condition). We examined object effects and distance effects, both when the object and target were present simultaneously in the display (Experiment 1a), and when the target appeared after the object disappeared (Experiment 1b).

If attention is automatically drawn to the object, performance is expected to be faster and/or more accurate in the Inside-object condition than in the Outside-object condition (an object effect). Also, performance is expected to be faster and/or more accurate in the Inside-object than in the No-object condition (a benefit), because attention is allocated in advance to the object, and slower and/or less accurate in the Outside-object condition than in the No-object condition (a cost), because presumably attention has to be redirected from the object to the target. If the automatic deployment of attention to the object involves a spatial component, such that attention is deployed to the spatial location of the object, the benefits of attention are expected to persist for a short time interval for targets occurring at the location previously occupied by the object (e.g., Kramer, Weber, & Watson, 1997), and therefore, similar effects of object conditions are expected to be observed in Experiment 1b as in Experiment 1a. Furthermore, the costs associated with the target appearance in a non-object location should increase when the target is located farther from the object (e.g., Kramer & Jacobson, 1991; Vecera & Farah, 1994).

2.1. Method

2.1.1. Observers

Observers in all experiments reported in this article were students at the University of Haifa. All observers provided informed consent to a protocol approved by the Ethics Committee of the Psychology Department at University of Haifa. All had normal or corrected-to-normal vision. Fourteen observers (19–29 years old, 1 male) participated in Experiment 1a, and 15 observers (20–25 years old, 6 male) participated in Experiment 1b.

2.1.2. Apparatus

All the experiments were conducted on a PC with a 17-in. CRT color monitor set at a resolution of $1,024 \times 768$ pixels and a refresh rate of 85 Hz, using E-Prime. Viewing distance was fixed at 60 cm with a chinrest.

2.1.3. Stimuli

The elements array ($18° \times 18°$) included 6×6 black *L* elements presented on a gray background (Fig. 1A–C). Each arm of the *L* element subtended $1.2° \times 0.15°$. The *L* element was pseudo-randomly rotated, unless it was part of an object, to one of 8 possible angles (0°, 45°, 90°, 135°, 180°, 225° 270°, 315°). The target was a Vernier stimulus composed of two $0.84° \times 0.15°$ vertical, black lines. One of the lines appeared 0.03° above the other line and was 0.09° horizontally displaced to the left or right of the lower line. A square-like object was formed by rotating four elements (Fig. 1A and B). There were eight possible locations (along the circumference of the elements matrix) in which the object could appear, hence eight possible target locations (Fig. 2A).

There were three critical object conditions. In the Inside-object condition (9% of total trials), an object was present in the display

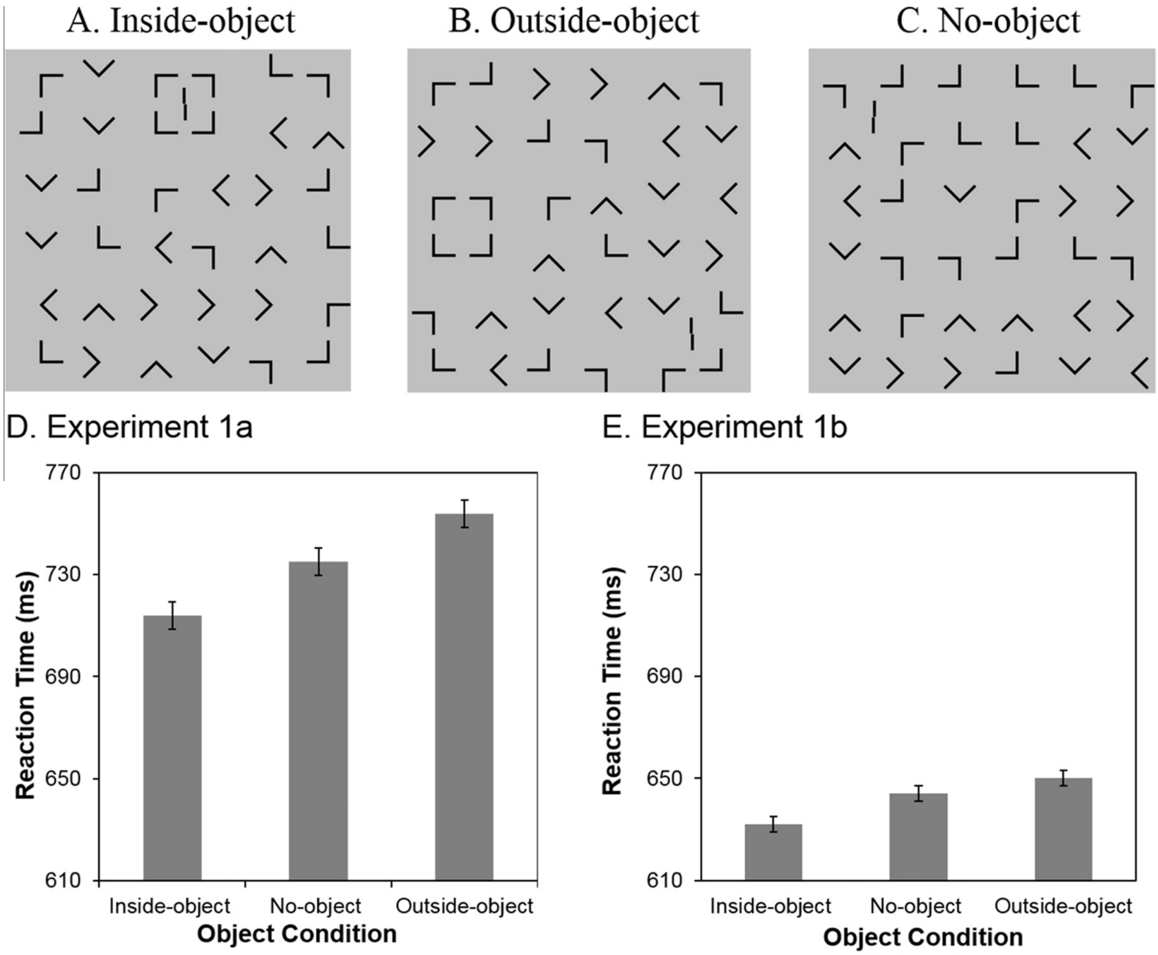

Fig. 1. Examples of the displays in the three conditions of Experiments 1a and 1b: (A) Inside-object condition (9% of all trials), an object is present in the display and the Vernier target appears in the center of the object. (B) Outside-object condition (64% of all trials), an object is present in the display but the Vernier target appears in a different location. (C) No-object condition (27% of all trials), no object is present in the display. Results: (D) mean correct RTs as a function of object condition in Experiment 1a and (E) in Experiment 1b. Error bars represent within subjects ± SEM.

and the target appeared in the center of the object (Fig. 1A). In the Outside-object condition (64% of total trials), an object was present in the display, but the target was presented in one of the other seven possible locations outside the object (Fig. 1B). In the No-object condition (27% of total trials) the elements did not form any object and the target appeared in one of the eight possible locations (Fig. 1C).[2]

The distance between the target and the object in the Outside-object condition, from the shortest to the longest, was 6.33° (28% of the distances), 9.18° (14% of the distances), 12.66° (21% of the distances), 14.15° (29% of the distances), and 17.9° (7% of the distances), as illustrated in Fig. 2A.

2.1.4. Procedure

Each trial began with a fixation dot appearing for 500-ms and followed by the elements display. In Experiment 1a, the target appeared 150 ms after the onset of the display and stayed on until response. In Experiment 1b, the elements display appeared for 100 ms, and after 50 ms the Vernier target appeared and stayed on until response. The observers had to indicate, as fast and accurately as possible, whether the upper line of the target was displaced to the right or left of the lower line by pressing one of two keys on the keyboard. Each observer participated in 40 practice trials and 1232 experimental trials.

2.2. Results and discussion

All reaction time (RT) summaries and analyses are based on observers' mean RTs for correct responses. RTs outside the range of 200–2000 ms were omitted from the analyses (0.35%, and 0.22% of all trials, in Experiments 1a and 1b, respectively). Mean RTs as a function of object condition are depicted in Fig. 1D (Experiment 1a) and Fig. 1E (Experiment 1b). Error rates (ERs) are presented in Table 1. ERs were very low, and there was no indication for speed–accuracy tradeoff. Therefore, error rates are not discussed further.

We first examined the effect of the presence of an object in the display on performance. A one-way (object condition: Inside-object, Outside-object, No-object) repeated measures ANOVA showed a significant effect of object condition [$F(2,26) = 14.94$, $p < .0001$, $\eta_p^2 = .53$; $F(2,28) = 8.59$, $p = .0012$, $\eta_p^2 = .38$, for Experiments 1a and 1b, respectively]. As can be seen in Fig. 1D and E, the pattern of results was similar in the two experiments. The observers made the fastest responses when the target appeared in the center of the object (Inside-object condition) and the slowest responses when the target appeared in a non-object location

[2] Given the large number of target and object locations in this experiment, the ratio of Inside-object trials to Outside-object trails is highly in favor of the Outside-object condition. In order to allow for a reasonable number of Inside-object trials while keeping a reasonable number of total trials, we reduced the number of No-object trials. Consequently, the object appeared more frequently, but it was not predictive of target's location.

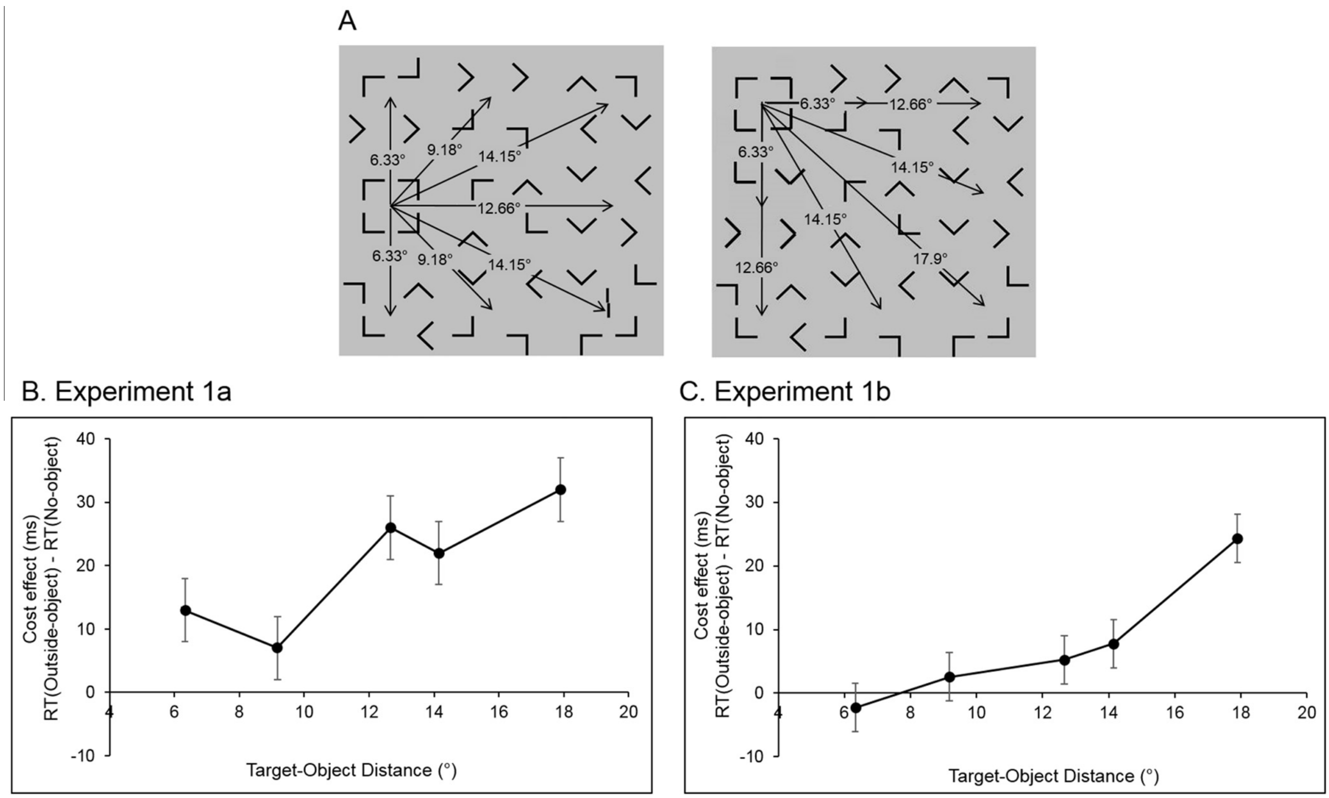

Fig. 2. (A) Examples of the target–object distances in the Outside-object condition in Experiments 1a and 1b. Results: (B) mean cost effects as a function of target–object distance for Experiment 1a and (C) for Experiment 1b. Error bars represent within subjects ± SEM.

Table 1
Error rates (Percentages) for each experiment as a function of object condition.

	Object condition		
	Inside-object	No-object	Outside-object
Experiment 1a	0.63	0.99	1.26
Experiment 1b	1.25	1.66	1.82
Experiment 2a	2.97	2.39	2.69
Experiment 2b	3.86	3.21	3.34
Experiment 2c	3.02	3.60	3.77
Experiment 2d	2.43	3.26	3.15
Experiment 3a	1.96	3.22	3.70
Experiment 3b	2.25	3.64	3.89
Experiment 3c	1.56	2.34	2.10
Experiment 3d	2.40	2.98	3.21

(Outside-object condition). Planned comparisons confirmed that observers were significantly faster in the Inside-object condition than in the Outside-object condition by 40 ms [$F(1,13) = 20.85$, $p = .0005$, $\eta_p^2 = .62$] in Experiment 1a, and by 17 ms [$F(1,14) = 13.40$, $p = .0026$, $\eta_p^2 = .49$] in Experiment 1b. Planned comparisons further revealed a significant benefit – responses in the Inside-object condition were faster than responses in the No-object condition by 21 ms [$F(1,13) = 9.40$, $p = .0107$, $\eta_p^2 = .36$] in Experiment1a, and by 12 ms [$F(1,14) = 5.10$, $p = .0405$, $\eta_p^2 = .27$] in Experiment 1b, and a significant cost – responses in the Outside-object condition were slower than responses in the No-object condition by 19 ms [$F(1,13) = 15.07$, $p = .0019$, $\eta_p^2 = .54$] in Experiment 1a, and by 6 ms [$F(1,14) = 5.99$, $p = .0282$, $\eta_p^2 = .30$] in Experiment 1b.

We turn now to examine the effect of the target–object distance on performance. To this end we compared the cost effect [RT (Outside-object condition) – RT(No-object condition)] for the five target–object distances. Mean cost effects as a function of target–object distance in Experiments 1a and 1b are presented in Fig. 2B and 2C, respectively.

The cost effects were significant for all target–object distances but 9.18° in Experiment 1a [$t(13) = 3.34$, $p = .0053$; $t(13) = 3.38$, $p = .0049$; $t(13) = 3.64$, $p = .0030$; $t(13) = 3.25$, $p = .0063$, for 6.33°, 12.66°, 14.15°, and 17.9°, respectively], and for 14.15° [$t(14) = 2.91$, $p = .0113$] and 17.9° [$t(14) = 4.25$, $p = .0008$] in Experiment 1b. In both experiments, the size of the cost effect depended on the distance between the target and the object: a one-way repeated measures ANOVA showed a significant effect of target–object distance [$F(4,52) = 3.38$, $p = .0156$, $\eta_p^2 = .21$; $F(4,56) = 7.11$, $p < .0001$, $\eta_p^2 = .34$, for Experiments 1a and 1b, respectively]. Planned comparisons conducted on the data of Experiment 1a showed a significantly larger cost when the target–object distance was 12.66° than 6.33° and 9.18° [$t(13) = 2.62$, $p = .0210$, $t(14) = 2.50$, $p = .0266$, respectively], 14.15° than 9.18° [$t(13) = 2.46$, $p = .0286$], and 17.9° than 9.18° [$t(13) = 2.16$, $p = .0498$]. Note that there was no significant difference in cost between the distances 6.33° and 9.18° [$t(13) = 1.2$, $p = .2504$], and between the distances 12.66° and 14.15° [$t < 1$]. In Experiment 1b, the cost for target–object distance of 17.9° was larger than the cost for the distances of 6.33°, 9.18°, 12.66°, and 14.15° [$t(14) = 3.50$, $p = .0035$; $t(14) = 3.83$, $p = .0018$; $t(14) = 3.08$, $p = .0081$; $t(14) = 2.86$, $p = .0124$, respectively].

The results of the present experiments agree with our previous results (Kimchi et al., 2007; Yeshurun et al., 2009), clearly demonstrating automatic capture of attention by the object. The presence of an object in the display influenced the discrimination of the direction of displacement in the Vernier target: Responses were the fastest when the target appeared within the object and the slowest when the target appeared in a non-object location, and both the benefit and cost effects were significant. These effects were observed despite the fact that the object was completely irrelevant to the task, not predictive of target and of target's location, and was not associated with abrupt onset or any other unique transient, thus indicating stimulus-driven attentional capture by the object.

The object effects obtained when the target appeared after the object disappeared (Experiment 1b) were somewhat smaller than when the target and the object were present simultaneously in the display (Experiment 1a), but the pattern of results was similar, showing a significant benefit when the target appeared at the location previously occupied by the object and a significant cost when the target appeared at other locations. Also, in both experiments, the cost accrued when the target appeared in a non-object location increased with an increase in the target–object distance. These two findings indicate the involvement of a spatial component: The deployment of attention to the object is accompanied with a deployment of attention to the spatial locations occupied by the object.

These results are consistent with several previous studies showing that attentional selection can be both space-related and object-related (e.g., Egly et al., 1994; Humphreys & Riddoch, 2003; Kravitz & Behrmann, 2008; Shomstein & Behrmann, 2006; Vecera & Farah, 1994). Of particular relevance is the finding of Humphreys and Riddoch (2003) who showed that given two stimuli, a closed and a non-closed shape, the simultanagnosic patient G.K. tended to perceive the closed shape, and the identification of a subsequently presented letters was more accurate for letters falling at the location of the closed shape than for letters at the other location, even though G.K.'s explicit localization judgments were at chance. Humphreys and Riddoch interpreted these findings as indicating that the object-based bias to select the closed shape in turn biased spatial attention, thus consistent with a joint influence of object-related and space-related selection.

There are also studies that show that selection can be based on spatial and featural representations simultaneously (e.g., Harms & Bundesen, 1983; Kim & Cave, 2001), and even on the basis of multiple representations – spatial, object, and featural (Kravitz & Behrmann, 2011). Although there has been a debate whether attention is object-based or space-based and whether one mode is more important than the other (e.g., Kramer et al., 1997; Lavie & Driver, 1996; Vecera, 1994), the above-mentioned findings and other findings reported in the literature have led to the emerging view that different attentional modes coexist in the visual system and may influence one another (e.g., Kravitz & Behrmann, 2011; Mozer & Vecera, 2005).

3. Study 2: Experiments 2a–2d

Having demonstrated, across different displays and tasks (Experiments 1a and 1b; Kimchi et al., 2007; Yeshurun et al., 2009), that a perceptual object can capture attention automatically, we can examine which organization factors suffice for an object to capture attention. To this end we created displays in which the object was organized by different Gestalt factors. An organization by three Gestalt factors – collinearity, closure, and symmetry, as used in all our previous experiments, served as a benchmark (Experiment 2a, Fig. 3A and B). The other organizations included an organization by closure and symmetry (Experiment 2b, Fig. 4A and B), organization only by collinearity (Experiment 2c, Fig. 5A and B), and organization only by symmetry (Experiment 2d, Fig. 6A and B). We presented observers with a display of 16 black elements in various orientations. One of the elements changed its color from black to red or orange 150 ms following the onset of the display. The task was to identify the color of the changed element (the target). A subset of the elements formed an object on some of the trials, and the target could be an object's element or a non-object element. As in our previous experiments, the object was completely task irrelevant, not predictive of the target, and was not associated with any unique transient.

3.1. Method

3.1.1. Observers

Sixteen individuals (20–27 years old, 6 males) participated in Experiment 2a, 14 individuals (19–30 years old, 6 males) participated in Experiment 2b, 15 individuals (19–25, 2 males) participated in Experiment 2c (one observer was excluded from the analysis due to speed-accuracy tradeoff), and 14 individuals (18–24, 2 males) participated in experiment 2d. None participated in Experiments 1a or 1b.

3.1.2. Stimuli

Experiment 2a: The elements display ($12° \times 12°$) included 4×4 black *L* elements presented on a gray background. Each arm of the *L* element subtended $1.2° \times 0.15°$, and the *L* element was pseudo-randomly rotated to one of 8 possible angles (in steps of 45°). The target was an *L* element that changed its color from black to red (RGB: 255,0,0) or to orange (RGB: 255,128,64). On half of the trials four elements were rotated such that they were collinear, forming a nearly closed, symmetric object – a square (Fig. 3A and B). There were four possible locations where the object could appear (excluding the center and the corners of the elements display), hence there were 12 possible target elements. On 12.5% of all trials the target was an object's element (Inside-object condition, Fig. 3A).[3] On 37.5% of all trials the target was a non-object element (Outside-object condition, Fig. 3B). On 50% of all trials the elements did not form an object, and the target was one of the twelve possible target-elements (No-object condition, Fig. 3C).

Experiment 2b: The elements display included 4×4 black line elements. Each line element subtended $2.4° \times 0.15°$, and was pseudo-randomly rotated to one of 8 possible angles (in steps of 22.5°). The target was a line that changed its color from black to red or to orange. On half of the trials, four elements were rotated to form a nearly closed, symmetric diamond-like object (Fig. 4A and B). Inside-object trials occurred on 12.5% of all trials (Fig. 4A), 37.5% of all trials were Outside-object trials (Fig. 4B), and 50% of all trials were No-object trials (Fig. 4C).

Experiment 2c: The elements display was the same as in Experiment 2a. On half of the trials three elements were collinear, forming a step-like object (Fig. 5A and B). The target was the central element in the object, which changed its color from black to red or orange. There were eight possible object locations, hence there were 8 possible target locations. Inside-object trials occurred on 6.25% of all trials (Fig. 5A), 43.75% of all trials were Outside-object trials (Fig. 5B), and 50% of all trials were No-object trials (Fig. 5C).

Experiment 2d: The elements display was the same as in Experiment 2a. On half of the trials four elements were rotated to form a symmetric plus-like object (Fig. 6A and B). The object and target possible locations were also the same as in Experiment 2a. Inside-object trials occurred on 12.5% of all trials (Fig. 6A), 37.5% of all trials were Outside-object trials (Fig. 6B), and 50% of all trials were No-object trials (Fig. 6C).

3.1.3. Procedure

Each trial began with a fixation dot appearing for 500-ms and

[3] In determining the frequencies, twice as much weight is given to the outer elements of an object because the outer ones appear only in one object, whereas the inner elements appear in two objects (e.g., see the upper right element of the object in Fig. 3A and the lower left element of the object in Fig. 3B: the same element appearing in two objects).

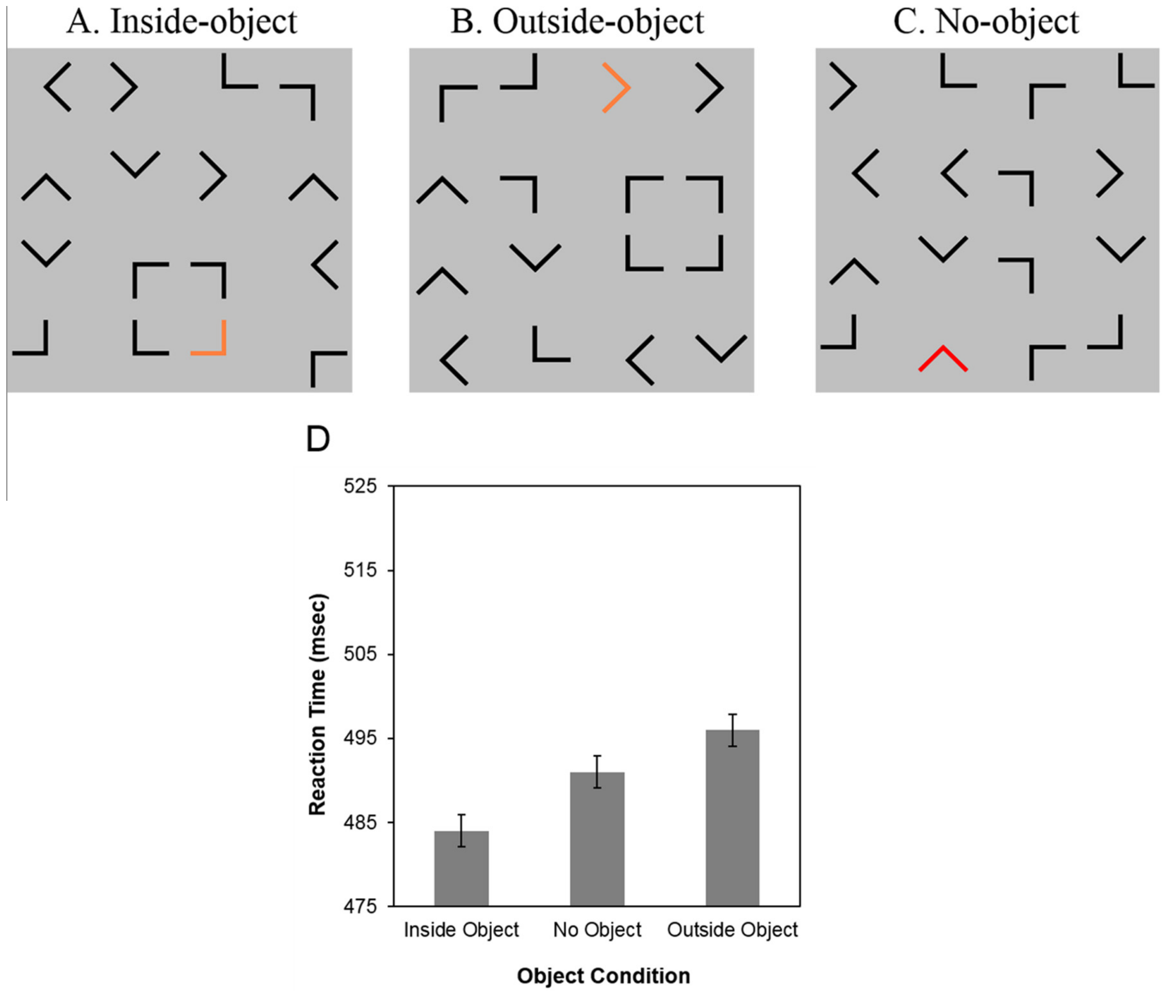

Fig. 3. Examples of the displays in the three conditions of Experiment 2a – object defined by closure, collinearity, and symmetry: (A) Inside-object condition (12.5% of the trials), an object is present in the display and one of the object's elements changes its color. (B) Outside-object condition (37.5% of the trials), an object is present in the display but a non-object element changes it color. (C) No-object condition (50% of the trials), no object is present in the display. Results for Experiment 2a: (D) mean correct RTs as a function of object condition. Error bars represent within subjects ± SEM.

followed by the elements display. One of the elements changed its color from black to red or orange 150 ms after the onset of the matrix, and stayed on until response. The observers had to indicate, as fast and accurately as possible, the color of the changed element (the target). There were 40 practice trials and 1152 experimental trials in Experiments 2a, 2b, and 2d, and 1024 experimental trials in Experiment 2c.

3.2. Results and discussion

RTs outside the range of 200–1200 ms were omitted from the analyses (0.64%, 1.10%, 0.91%, and 2.12% of all trials, in Experiments 2a, 2b, 2c, and 2d, respectively). Mean correct RTs as a function of object condition are presented in Fig. 3D (Experiment 2a), Fig. 4D (Experiment 2b), Fig. 5D (Experiment 2c), and Fig. 6D (Experiment 2d). ERs are presented in Table 1 (Experiments 2a–2d). The RT data were submitted to one-way (object condition) repeated measures ANOVA. Object effects were evaluated by planned comparisons. Similar analyses that were conducted on the ERs did not yield any significant results.

Experiment 2a: The ANOVA showed a significant effect of object condition [$F(2,30) = 9.61$, $p = .0006$, $\eta_p^2 = .39$]. As can be seen in Fig. 3D, observers were the fastest when the target was an element of the object (Inside-object condition) and the slowest when the target was a non-object element (Outside-object condition), indicating an object effect [$F(1,15) = 13.48$, $p = .0023$, $\eta_p^2 = .47$]. There was also a significant benefit – faster responses in the Inside-object condition than in the No-object condition [$F(1,15) = 4.59$, $p = .0491$, $\eta_p^2 = .23$], and a significant cost – slower responses in the Outside-object condition than in the No-object condition [$F(1,15) = 10.71$, $p = .0051$, $\eta_p^2 = .41$].

These results converge with the results of Experiments 1a and 1b and with our previous results (Kimchi et al., 2007; Yeshurun et al., 2009), demonstrating once again that a perceptual object organized by collinearity, closure, and symmetry captures attention automatically.

Experiment 2b: The analysis showed a significant effect of object condition [$F(2,26) = 7.28$, $p = .0031$, $\eta_p^2 = .36$]. As can be seen in Fig. 4D, an object effect was also observed when the object is organized by closure and symmetry: responses were significantly faster in the Inside-object condition than in the Outside-object condition [$F(1,13) = 11.35$, $p = .005$, $\eta_p^2 = .47$]. There was also a significant benefit [$F(1,13) = 9.35$, $p = .0092$, $\eta_p^2 = .42$], but no significant cost, $F < 1$.

Experiment 2c: A significant effect of object condition was also observed when the object was organized only by collinearity [$F(2,28) = 4.19$, $p = .0256$, $\eta_p^2 = .23$]. As can be seen in Fig. 5D, responses were faster in the Inside-object condition than in the

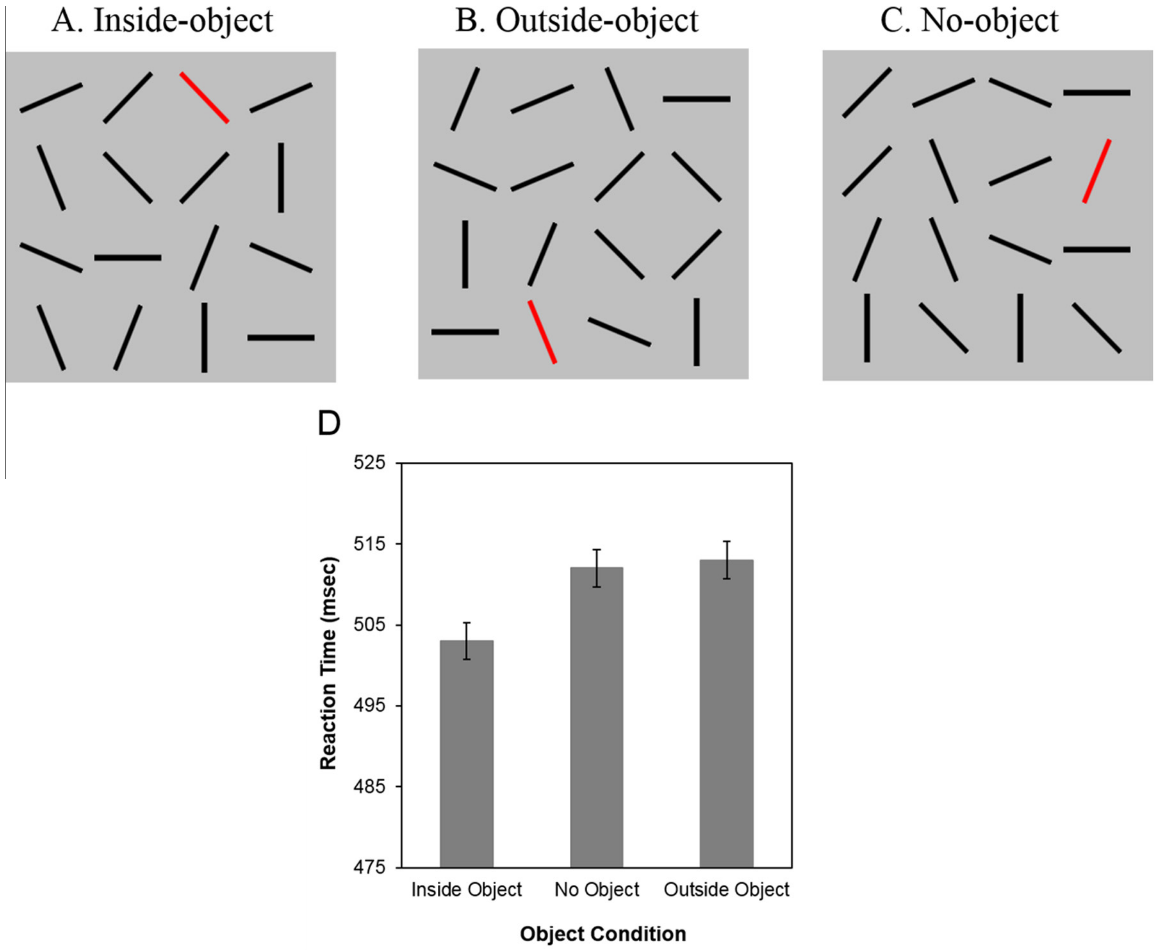

Fig. 4. Examples of the displays in the three conditions of Experiment 2b – object defined by closure and symmetry. (A) Inside-object condition (12.5% of the trials). (B) Outside-object condition (37.5% of the trials). (C) No-object condition (50% of the trials). Results for Experiment 2b: (D) mean correct RTs as a function of object condition. Error bars represent within subjects ± SEM.

Outside-object condition, indicating an object effect [$F(1,14) = 5.28$, $p = .0375$, $\eta_p^2 = .27$]. There was also a significant cost [$F(1,14) = 9.28$, $p = .0087$, $\eta_p^2 = .40$], but no significant benefit, $F < 1$.

Experiment 2d: Presence or absence of an object in the display had no effect on performance when the object was organized only by symmetry (Fig. 6D), $F < 1$.

The results show some differences in the effects of benefit and cost between Experiments 2a, 2b, and 2c: both effects were statistically significant for Experiment 2a, but only the benefit effect for Experiment 2b, and the cost effect for Experiment 2c, reached statistical significance. Nonetheless, the pattern of results in these three experiments was very similar, with the fastest responses observed when the target was an object's element and the slowest when the target was a non-object element. That is, for all three experiments, responses were significantly faster in the Inside-object condition than in the Outside-object condition, indicating a significant object effect for each experiment. On the other hand, the findings of Experiment 2d differed markedly from those of the other three experiments, with no indication whatsoever of an effect of the object on performance.

In order to directly compare the capture of attention by the perceptual object in the four experiments, we calculated the object effect [RT(Outside-object) - RT(Inside-object)] for each subject in each of the experiments. The mean object effect for each experiment is presented in Fig. 7. A one-way between-subjects ANOVA showed a significant effect of experiment [$F(3,55) = 2.96$, $p = .0403$, $\eta_p^2 = .14$]. Planned comparisons revealed that the object effect in Experiment 2d differs significantly from the one in Experiment 2a [$t(28) = 2.98$, $p = .0058$], Experiment 2b [$t(26) = 2.68$, $p = .0124$], and Experiment 2c [$t(28) = 2.07$, $p = .0477$], and no differences were observed between Experiments 2a, 2b, and 2c [$ts < 1$].

The present results show that organization by collinearity and organization by closure combined with symmetry, each produced object effects that were similar in magnitude to the one produced when collinearity, closure, and symmetry were combined. In contrast, organization by symmetry alone failed to produce an object effect. These findings suggest that grouping by collinearity or by closure (at least when combined with symmetry), suffices for automatic, stimulus-driven attentional capture, but grouping by symmetry does not.

It is possible that the failure of the grouping by symmetry to capture attention is related to our specific stimuli. In the object formed by symmetry (see Fig. 6A and B), the spacing between the elements within the object turned out to be larger than some of the spacing between the object's elements and nearby elements. Given that proximity is considered a very powerful cue (e.g., Elder & Goldberg, 2002; Kubovy & van den Berg, 2008), it could weaken the organization by symmetry, and thereby its ability to capture attention.

Notwithstanding this possibility, the present findings appear to be consistent with previous findings demonstrating the contribu-

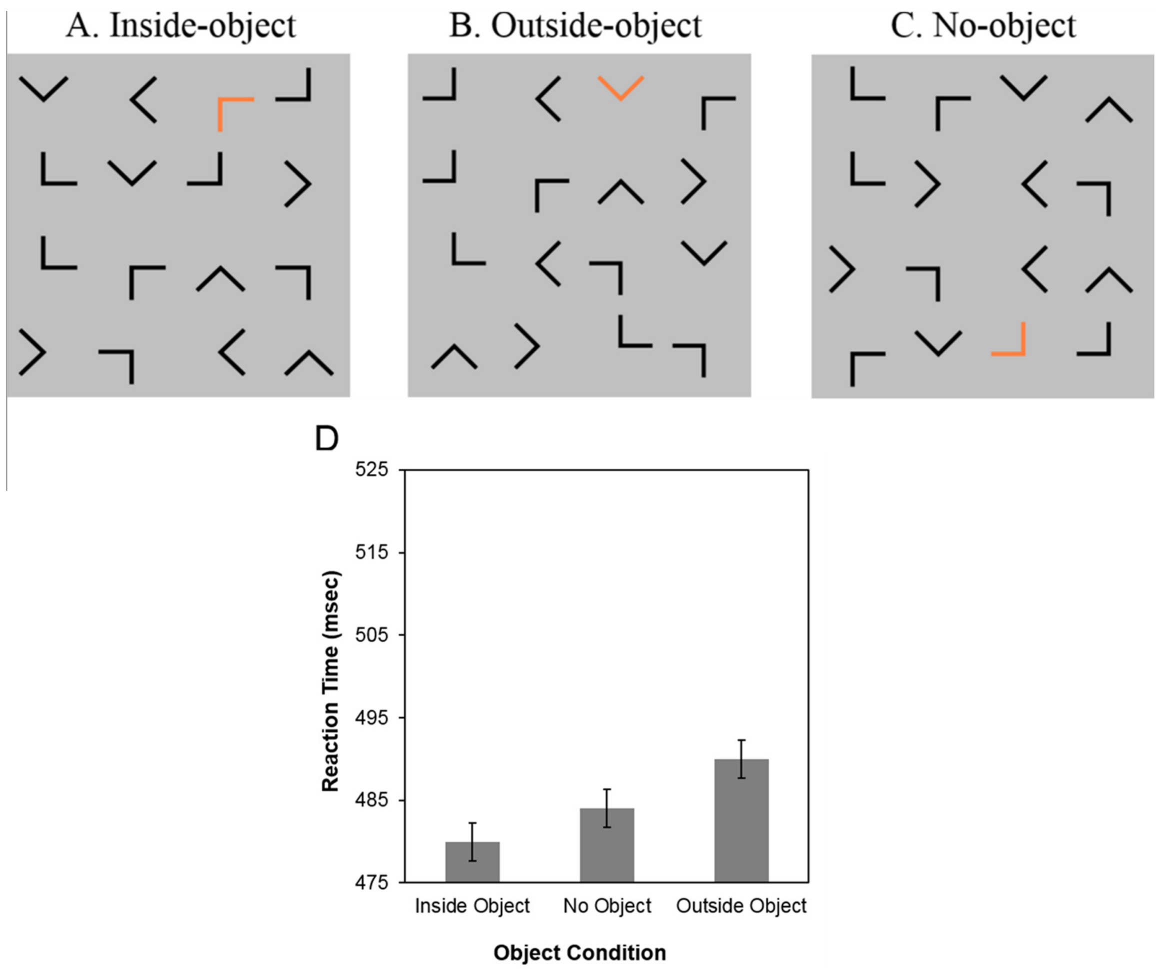

Fig. 5. Examples of the displays in the three conditions of Experiment 2c – object defined by collinearity only. (A) Inside-object condition (6.25% of the trials). (B) Outside-object condition (43.75% of the trials). (C) No-object condition (50% of the trials). Results for Experiment 2c: (D) Mean correct RTs as a function of object condition. Error bars represent within subjects ± SEM.

tion to perceptual grouping for collinearity and closure, whereas no clear contribution to perceptual organization was demonstrated for symmetry. For example, several studies demonstrated the important role of collinearity in contour integration and interpolation (e.g., Field, Hayes, & Heiss, 1993; Geisler, Perry, Super, & Gallogly, 2001; Kellman & Shipley, 1991). Closure also plays an important role in contour integration (e.g., Kovacs & Julesz, 1993; Mathes & Fahle, 2007; but see Tversky, Geisler, & Perry, 2004) and in grouping of shape (e.g., Elder & Zucker, 1993; Hadad & Kimchi, 2008). In addition, in experiments designed to reveal the emergence of organizational processes using a primed matching task with line configurations, Kimchi (2000) showed that collinearity and closure were important in the initial organization.

Symmetry was identified by the Gestaltists as a figural cue, although it seems to be easily overruled by convexity (Kanizsa & Gerbino, 1976; but see Mojica & Peterson, 2014). Many studies showed that detection of mirror symmetry is fast and accurate (e.g., Barlow & Reeves, 1979; Wagemans, 1995), but it has been argued that grouping based on other principles precedes and facilitates symmetry detection (e.g., Hulleman & Humphreys, 2004b; Labonte, Shapira, Cohen, & Faubert, 1995; Pashler, 1990). For example, Hulleman and Humphreys showed that symmetry judgments were influenced by the figural cue of top–bottom polarity: Bilateral symmetry judgments were faster for shapes having wide bases than for shapes having wide tops. Machilsen, Pauwels, and Wagemans (2009) showed better detection of symmetric shapes than asymmetric ones in arrays of oriented Gabor elements, suggesting that vertical mirror symmetry facilitates figure-ground segregation, but the detection of symmetry could only follow the local grouping by collinearity of the Gabor elements. Also, accuracy of symmetry detection decreases with eccentricity (Gurnsey, Herbert, & Kenemy, 1998), suggesting that symmetry may not be a good cue for segmentation of the visual scene. Recently, Pomerantz and Portillo (2011) found that discrimination of symmetry's presence and its axis produced both configural superiority and configural inferiority effects, thus providing inconsistent evidence for symmetry as an emergent feature, and Devinck and Spillmann (2013) found that convexity dominated figure–ground segregation, while symmetry contributed little. All these findings cast some doubt on the role of symmetry in perceptual organization.

4. Study 3: Experiments 3a–3d

The aim of these experiments was to examine whether the stimulus-driven attentional capture by an object is influenced by the strength of perceptual organization. To this end we employed Kanizsa-type illusory figures (Kanizsa, 1976), and manipulated the spatial distribution of elements of opposite contrast polarity, which seems to influence the grouping of inducing elements in modal completion (e.g., Spehar, 2000). Using an illusory shape discrimination task (Ringach & Shapley, 1996), it has been shown

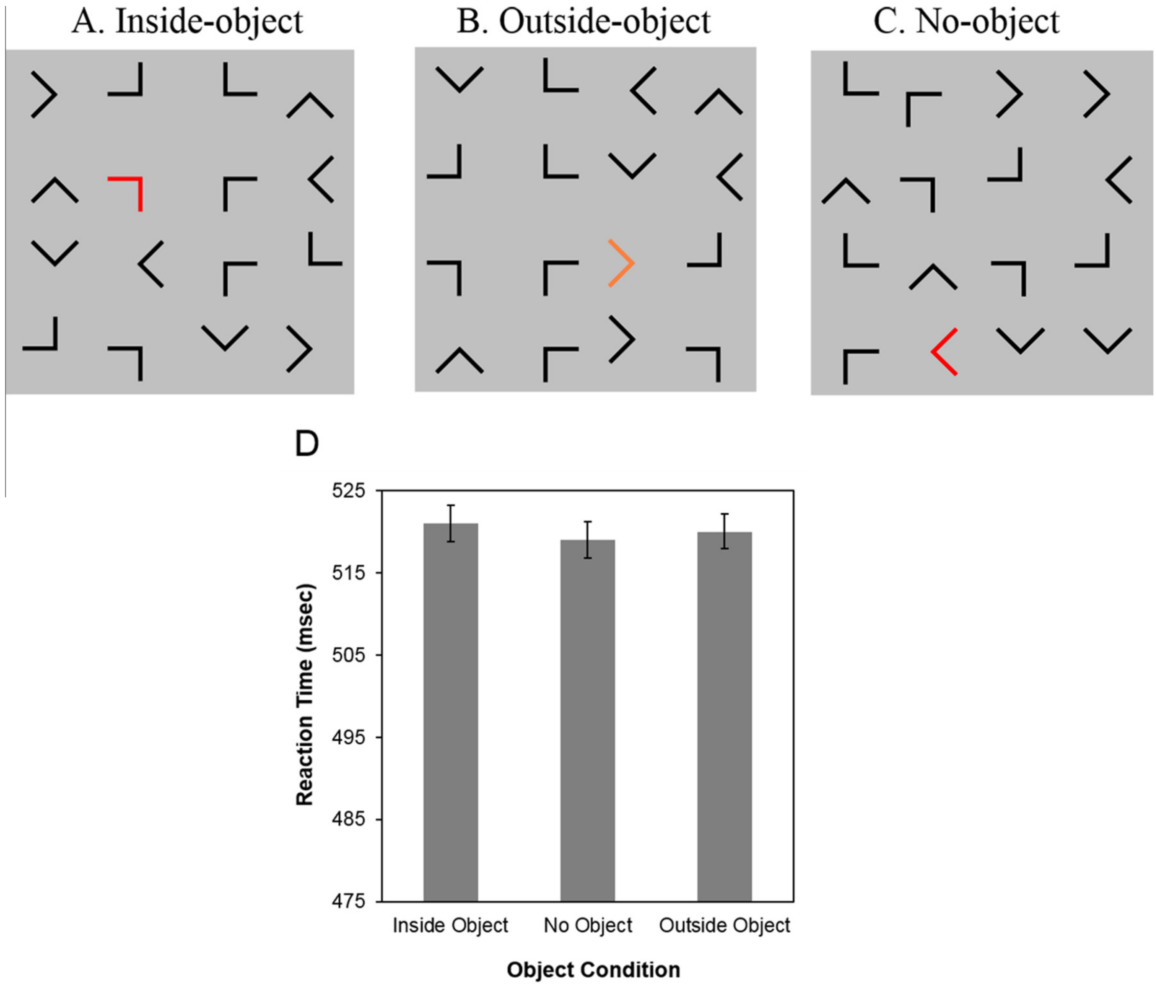

Fig. 6. Examples of the displays in the three conditions of Experiment 2d – object defined by symmetry only. (A) Inside-object condition (12.5% of the trials). (B) Outside-object condition (37.5% of the trials). (C) No-object condition (50% of the trials). Results for Experiment 2d: (D) mean correct RTs as a function of object condition. Error bars represent within subjects ± SEM.

that illusory contours were equally strong whether inducing elements were of the same contrast polarity or of opposite contrast polarity (Spehar, 1999, 2000; Victor & Conte, 1998), consistent with the view that grouping of collinear inducers is not sensitive to reversals in contrast polarity between the collinear inducers (e.g., Shapley & Gordon, 1985). However, illusory contour strength was significantly impaired when contrast polarity reverses at the intersections of orthogonally oriented edges within each inducer, at least for relatively short stimulus duration (Spehar, 1999, 2000; Spehar & Clifford, 2003), indicating that grouping is disturbed when the change in contrast polarity coincides with change in edge orientation.

In the following experiments, observers were presented with a display of 16 pacmen in various orientations. On half of the trials, four pacmen were collinear, forming a Kanizsa-type illusory square object. The pacmen were either all black, so the inducers of the illusory object were of the same contrast polarity (Experiment 3a, Fig. 8A and B), of opposite contrast polarity (half of the pacmen black and half white), and the change in contrast polarity occurred between collinear inducers of the illusory object (Experiment 3b, Fig. 9A and B), or each individual pacman contained segments of opposite contrast polarity, and the change in contrast polarity occurred at the corners of the illusory object, i.e., it coincided with points at which edges of different orientation intersect (Experiments 3c and 3d, Fig. 10A and B and Fig. 11A and B). The target was a Vernier stimulus, and it could appear within the object (12.5% of all trials) or in a non-object location (37.5% of all trials).

If the ability of a perceptual object to capture attention automatically is affected by the strength of perceptual organization (modal completion in the present case), then larger object effects are expected to be observed when the pacmen inducing the illusory object are all uniform, either of the same contrast or of opposite contrast polarity (Experiments 3a and 3b) than when contrast polarity varies within each pacman such that the changes in contrast polarity within the inducing configuration coincide with changes in the edge orientation (Experiments 3c and 3d).

4.1. Method

4.1.1. Observers

Twelve observes (22–30 years old, 5 males) participated in Experiment 3a, 12 observers (20–30 years old, 4 males) participated in Experiment 3b, 12 observers (23–30 years old, 4 males) participated in Experiment 3c, and 12 observers (20–28 years old, 4 males) participated in Experiment 3d (one observer in this experiment was excluded from the analysis because he had neglect of the left visual field). None participated in any of the previous experiments.

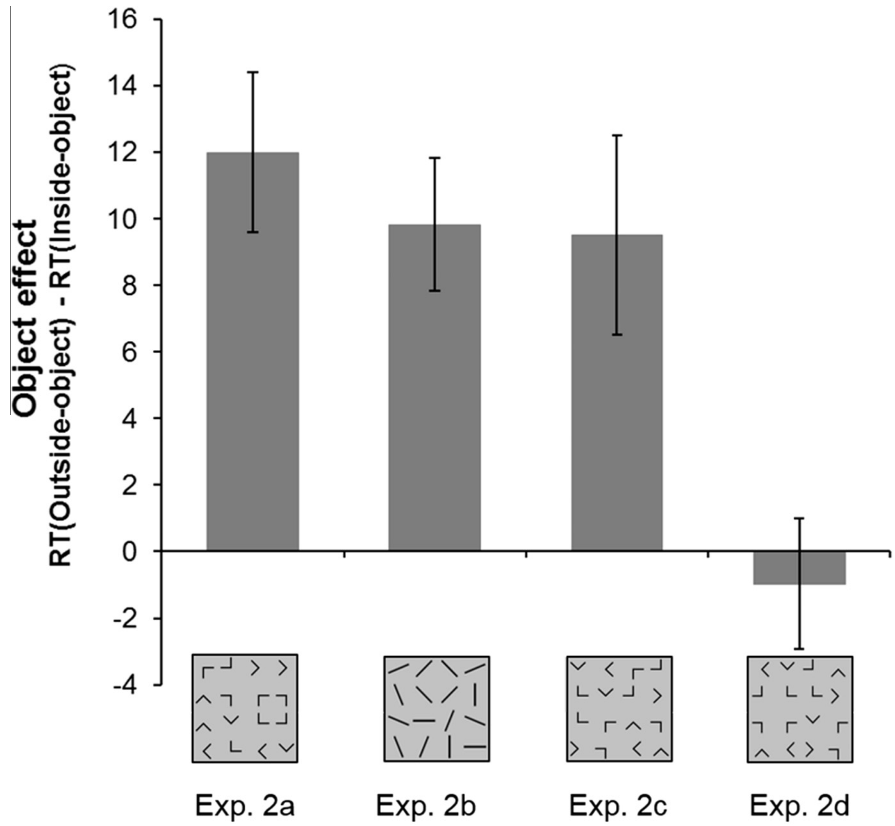

Fig. 7. Object effect [RT(Outside-object) – RT(Inside-object)] in Experiments 2a (collinearity + closure + symmetry), 2b (closure + symmetry), 2c (collinearity), and 2d (symmetry). The object effect was significant in Experiments 2a, 2b, and 2c; no object effect was observed in Experiment 2d. Error bars represent ± SEM.

4.1.2. Stimuli

The elements display in all four experiments included 4 × 4 pacmen, each subtended 1.71° in diameter. Each pacman was pseudo-randomly rotated to one of 8 possible angles (in steps of 45°). The Vernier target was composed of two 0.84° × 0.15° vertical, black lines. One of the lines appeared 0.03° above the other line and was 0.09° horizontally displaced to the left or right of the lower line. On half of the trials, four pacmen were rotated such that they were collinear, forming a Kanizsa-type illusory configuration – an illusory square object (e.g., Fig. 8A, Fig. 9A, Fig. 10A and Fig. 11A). There were four possible locations where the object could appear (excluding the corners and the center of the elements display), hence there were 4 possible target locations. On 12.5% of all trials the target appeared in the center of the object (Inside-object condition), on 37.5% of all trials the object was present and the target was presented in one of the other three possible non-object locations (Outside-object condition), and on 50% of all trials the pacmen did not form any illusory object and the target appeared in one of the four possible locations (No-object condition).

Experiment 3a: The elements display included black pacmen (Fig. 8A–C). Thus, the four pacmen forming the illusory object were all of the same contrast, as in the classical Kanizsa configuration.

Experiment 3b: The elements display included pacmen of opposite contrast polarity: half of the pacmen were black and half were white, with luminance of 0.5 cd/m^2 and 83 cd/m^2, respectively, presented on a gray background whose luminance was 54 cd/m^2 (Fig. 9A–C). The illusory square object was formed by two black and two white pacmen, such that the pacmen lying on the two diagonals were of opposite contrast polarity (Fig. 9A and B).

Experiments 3c: Each individual pacman contained segments of opposite contrast polarity (Fig. 10A–C). Thus, contrast polarity varied between spatially separate pacmen inducing the illusory object, as well as within each local pacman, but contrast polarity was preserved between spatially separated collinear segments (Fig. 10A and B).

Experiment 3d: The elements display was the same as in Experiment 3c. The only difference is that contrast polarity varied also across the spatially separated collinear segments of the pacmen inducing the illusory object (Fig. 11A and B).

4.1.3. Procedure

Each trial began with a fixation dot appearing for 500 ms and followed by the elements display. A Vernier target appeared in one of the four possible locations 150 ms after the onset of the display, and stayed on until response. The observers had to indicate, as fast and accurately as possible, whether the upper line of the target was displaced to the right or left of the lower line by pressing one of two keys on the keyboard. There were 32 practice trials and 1152 experimental trials.

4.2. Results and discussion

RTs outside the range of 200–1200 ms were omitted from the analyses (1.32%, 1.32%, 0.43%, and 1.57% of all trials, in Experiments 3a, 3b, 3c, and 3d, respectively). Mean correct RTs as a function of object condition are presented in Fig. 8D (Experiment 3a), Fig. 9D (Experiment 3b), Fig. 10D (Experiment 3c), and Fig. 11D (Experiment 3d). ERs are presented in Table 1 (Experiments 3a–3d). The RT data were submitted to one-way (object condition)

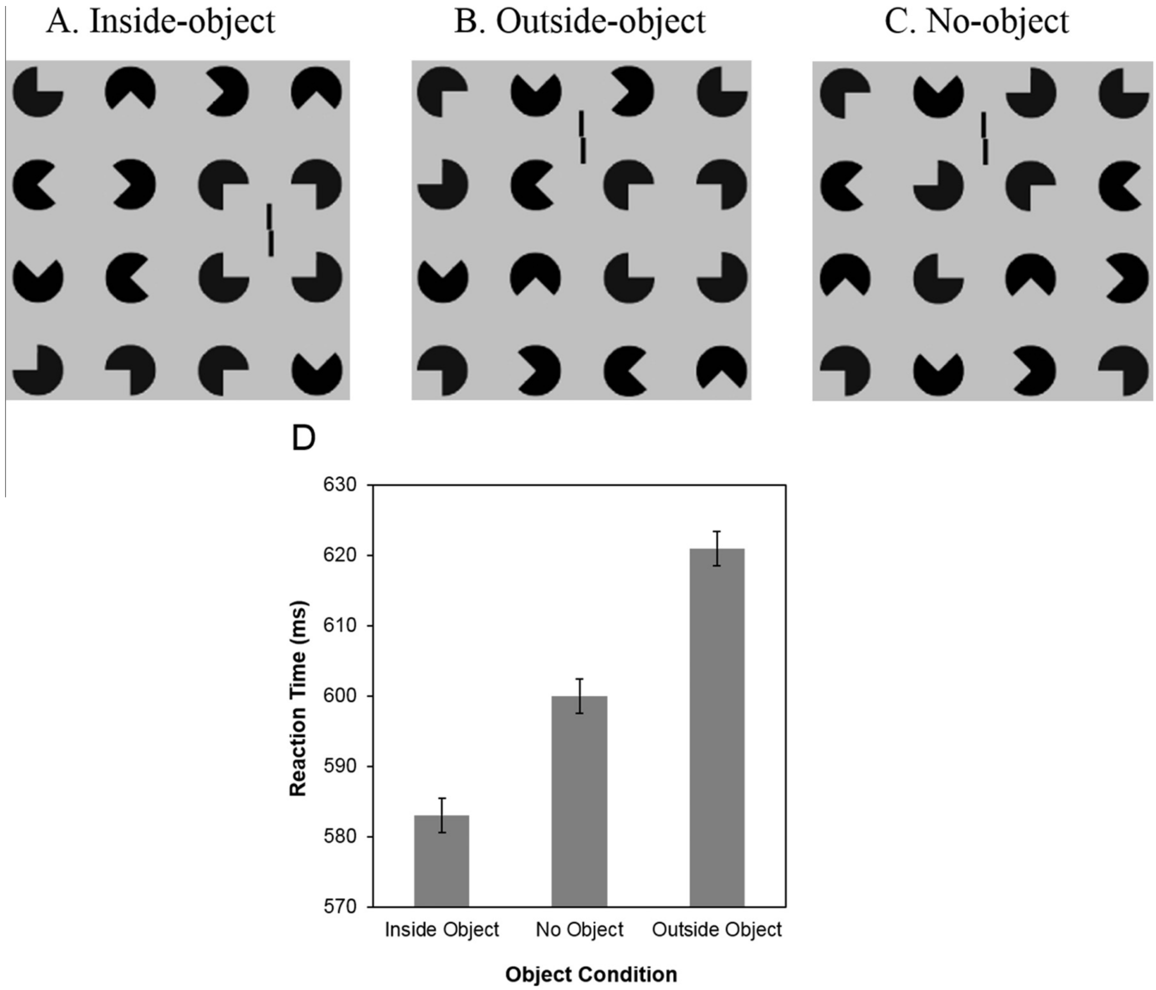

Fig. 8. Examples of the displays in the three conditions of Experiment 3a. (A) Inside-object condition (12.5% of the trials). (B) Outside-object condition (37.5% of the trials). (C) No-object condition (50% of the trials). Results for Experiment 3a: (D) mean correct RTs as a function of object condition. Error bars represent within subjects ± SEM.

repeated measures ANOVA. Object effects were evaluated by planned comparisons. Similar analyses were conducted on the ERs. The ERs showed similar trends as the RTs, but not all effects were statistically significant.

Experiment 3a: The analyses showed a significant effect of object condition [$F(2,22) = 58.83$, $p < .0001$, $\eta_p^2 = .86$, for RT; $F(2,22) = 7.34$, $p = .0036$, $\eta_p^2 = .40$, for ER]. Responses were 37 ms faster and error rate was 1.74% lower in the Inside-object condition than in the Outside-object condition [$F(1,11) = 73.91$, $p < .0001$, $\eta_p^2 = .87$, for RT; $F(1,11) = 9.86$, $p = .0094$, $\eta_p^2 = .47$, for ER], indicating an object effect (Fig. 8D). There was also a significant benefit – 16-ms faster responses and 1.26% lower ER in the Inside-object than in the No-object condition [$F(1,11) = 31.64$, $p = .0002$, $\eta_p^2 = .74$, for RT; $F(1,11) = 10.64$, $p = .0076$, $\eta_p^2 = .50$, for ER], and a significant cost for RT only – 21-ms slower responses in the Outside-object than in the No-object condition [$F(1,11) = 51.82$, $p < .0001$, $\eta_p^2 = .82$].

These results clearly show that an illusory object captures attention automatically, in a stimulus-driven fashion, much like a real object. A previous study (Senkowski, Rottger, Grimm, Foxe, & Herrmann, 2005) also suggested that Kanizsa illusory figures capture attention. However, the results of this study are subject to an alternative account, because the illusory object (a Kanizsa figure) and the target were both triangles; therefore, faster responses for targets appearing within the Kanizsa figure than for target appearing at another location, may reflect a controlled search for a triangle rather than a truly automatic deployment of attention to the Kanizsa figure. In the present experiment, on the other hand, there was no similarity between the illusory object and the target, and the object was completely task irrelevant, thus providing unequivocal evidence for the capture of attention by the illusory object.

Experiment 3b: As can be seen in Fig. 9D, the results for this experiment were similar to the ones observed for Experiment 3a. There was a significant effect of object condition [$F(2,22) = 25.65$, $p < .0001$, $\eta_p^2 = .70$, for RT; $F(2,22) = 7.03$, $p = .0004$, $\eta_p^2 = .38$, for ER]. Responses were 30 ms faster and ER was 1.64% lower when the target appeared in the center of the illusory object (Inside-object condition) than in a non-object location (Outside-object condition), indicating an object effect [$F(1,11) = 27.83$, $p = .0003$, $\eta_p^2 = .72$, for RT; $F(1,11) = 6.47$, $p = .0273$, $\eta_p^2 = .37$, for ER]. There was also a significant benefit – 17-ms faster responses and 1.42% lower ER in the Inside-object than in the No-object condition [$F(1,11) = 31.74$, $p = .0002$, $\eta_p^2 = .74$, for RT; $F(1,11) = 10.30$, $p = .0083$, $\eta_p^2 = .47$, for ER], and a significant cost for RT only – 13-ms slower responses in the Outside-object than in the No-object condition [$F(1,11) = 15.23$, $p = .0025$, $\eta_p^2 = .58$].

Experiment 3c: The analysis of the RT data showed a significant effect of object condition [$F(2,22) = 5.57$, $p = .0111$, $\eta_p^2 = .33$]. The object effect observed in this experiment (Fig. 10D) appeared smaller than the one observed in the previous two experiments:

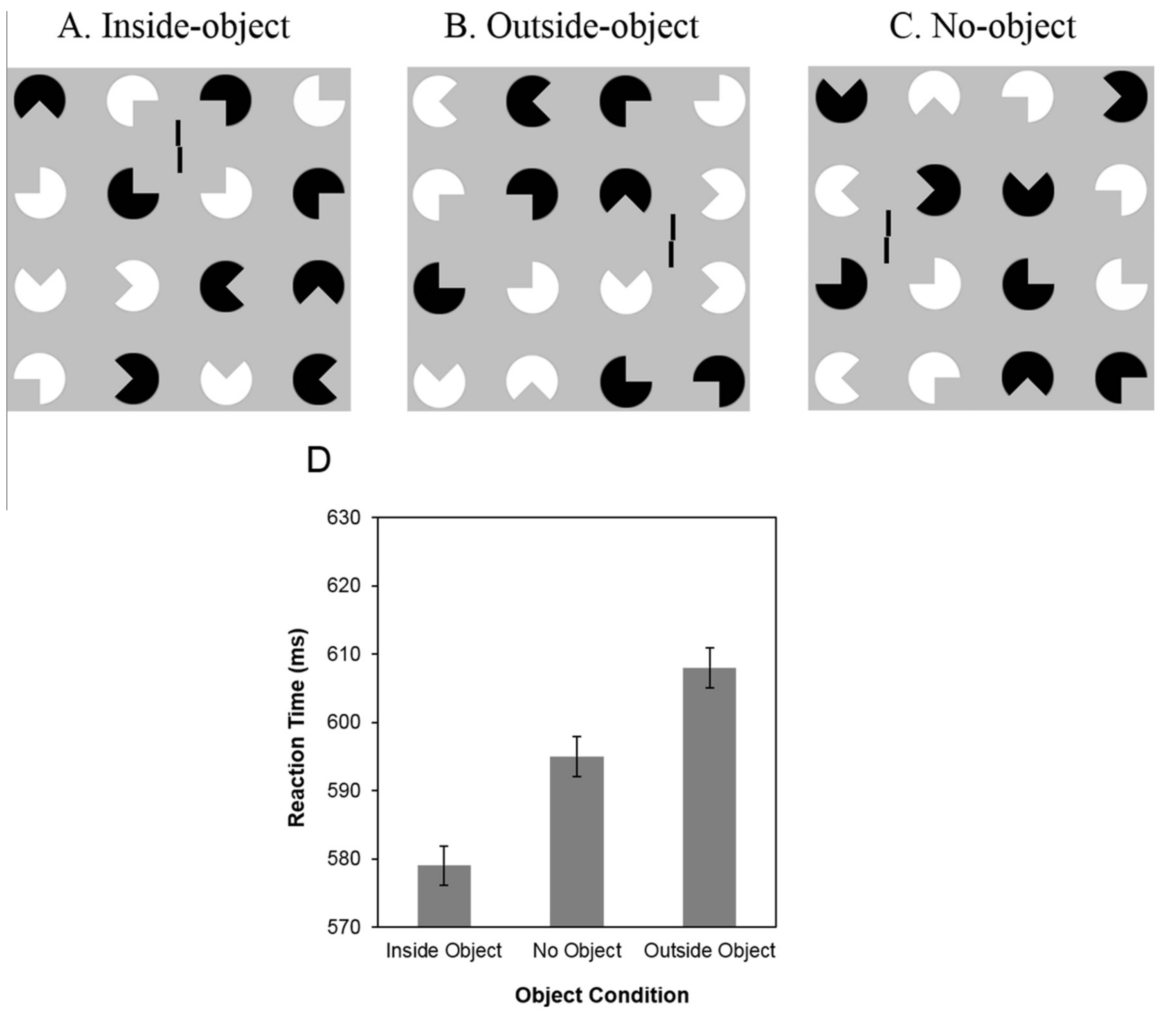

Fig. 9. Examples of the displays in the three conditions of Experiment 3b. (A) Inside-object condition. (B) Outside-object condition. Contrast polarity varies between spatially separate pacmen inducing the illusory object, but the contrast within each local pacman is uniform. (C) No-object condition. Results for Experiment 3b: (D) mean correct RTs as a function of object condition. Error bars represent within subjects ± SEM.

observers were 8 ms faster when the target appeared in the center of the illusory object (Inside-object condition) than when the target appeared in a non-object location (Outside-object condition) [$F(1,11) = 8.07$, $p = .0161$, $\eta_p^2 = .42$]. The benefit and cost effects did not reach statistical significance [$F(1,11) = 3.04$, $p = .1088$; $F(1,11) = 3.87$, $p = .0750$, respectively]. The ER data showed similar trends but none was statistically significant.

Experiment 3d: As can been in Fig 11D, the results were similar to the ones observed for Experiment 3c. The analysis of the RT data showed a significant effect of object condition [$F(2,20) = 3.50$, $p = .0496$, $\eta_p^2 = .26$]. Observers were 10 ms faster in the Inside-object condition than in the Outside-object condition, but the effect did not reach statistical significance [$F(1,10) = 3.71$, $p = .0831$, $\eta_p^2 = .27$]. There was a significant cost [$F(1,10) = 6.42$, $p = .0297$, $\eta_p^2 = .39$], but no benefit, $F < 1$. The ER data showed similar trends but none was statistically significant.

These results clearly show a similar pattern for Experiments 3a and 3b, on the one hand, and for Experiments 3c and 3d on the other hand, with a clear difference between these two pairs of experiments. Whereas the former two experiments yielded large object effects, the object effects in the latter two were much smaller, suggesting a difference in the ability to capture attention.

In order to directly compare the capture of attention by the illusory object in the different experiments, object effect [RT(Outside-object) – RT(Inside-object)] was calculated for each subject in each experiment. Mean object effect for each experiment is presented in Fig. 12. A one-way between-subject ANOVA showed a significant effect of experiment [$F(3,43) = 10.46$, $p < .0001$, $\eta_p^2 = .42$]. Planned comparisons revealed a significant difference between Experiments 3a and 3b versus Experiment 3c and 3d [$t(43) = 5.42$, $p < .0001$], with no difference between Experiments 3a and 3b [$t(22) = 1.11$, $p = .2758$], and between Experiments 3c and Experiment 3d [$t < 1$].

The strength of the illusory contours in Experiment 3a and 3b is assumed to be equal: although the inducers in Experiment 3a were all of the same contrast and those in Experiment 3b were of opposite contrast, change in contrast polarity in Experiment 3b occurred between collinear inducing pacmen. Therefore, the results for these two experiments were expected to be similar. Indeed, performance in these experiments was comparable, exhibiting the same object effects and of similar magnitude, indicating automatic attentional capture by the illusory object. Thus, when the strength of the illusory contours was equal, so was the ability of the illusory object to capture attention.

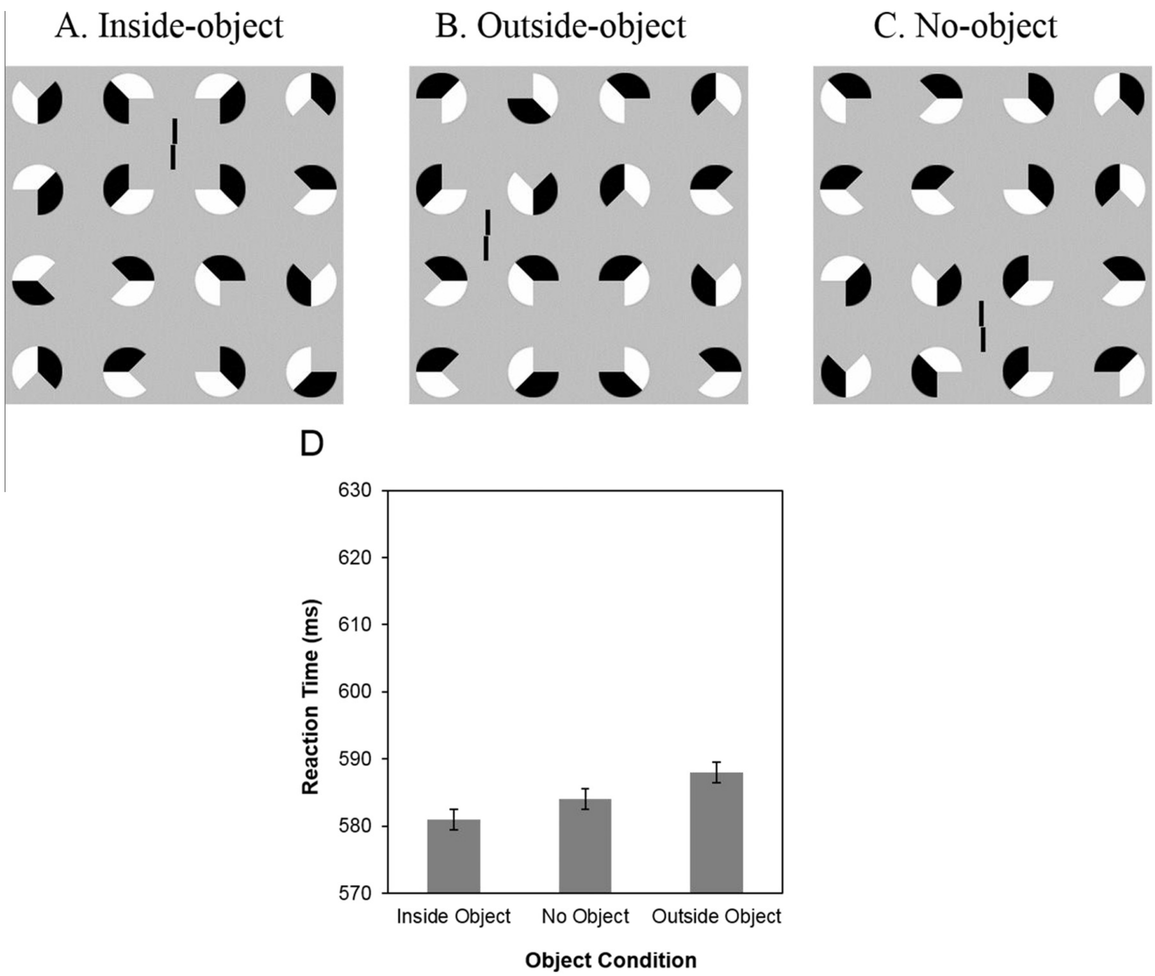

Fig. 10. Examples of the displays in the three conditions of Experiment 3c: (A) Inside-object condition. (B) Outside-object condition. Contrast polarity varies within each local pacman and between spatially separate pacmen inducing the illusory object, but it is preserved between spatially separated collinear segments. (C) No-object condition. Results for Experiment 3c: (D) mean correct RTs as a function of object condition. Error bars represent within subjects ± SEM.

In Experiments 3c and 3d, the strength of the illusory contours is assumed to be equally impaired, regardless of whether contrast polarity remained the same of changed between collinear inducers, because the critical factor is that the reversal in contrast polarity occurred at the corners of the illusory objects where there is a change in the edge orientation (e.g., Spehar, 2000). Accordingly, these two experiments were expected to yield similar results, but different from the ones for Experiments 3a and 3b, as was indeed the case: the object effect for Experiments 3c and 3d was similar, and of significantly smaller magnitude than the one observed for Experiments 3a and 3b.

These results clearly show that the strength of the grouping involved in modal completion affected the ability of the illusory object to capture attention.

5. General discussion

The goal of the studies reported in this article was to investigate the capture of attention by a perceptual object. In a series of experiments, we have demonstrated that when some of the elements in a display are organized by Gestalt factors into a coherent unit – an object – the presence of the object affects performance. Specifically, responses were significantly faster when a target appeared within the object than outside the object, despite the fact that the object was irrelevant to the task at hand, not predictive of the target, and was not associated with any unique transient. These results provide converging, unequivocal evidence that a perceptual object captures attention automatically, in a purely stimulus-driven manner. Taken together with previous findings (Kimchi et al., 2007; Yeshurun et al., 2009), the current findings demonstrate the robustness of this automatic attentional capture: It was obtained across different display sizes, different tasks, different frequencies of object trials, and with real and illusory objects. Importantly, such automatic, stimulus-driven capture of attention by an object may provide a single account for a variety of "object advantage" effects (e.g., Arrington, Carr, Mayer, & Rao, 2000; Driver & Baylis, 1996; Gorea & Julesz, 1990; Kovacs & Julesz, 1993; Weisstein & Harris, 1974) and "configural superiority" effects (Pomerantz, Sager, & Stoever, 1977), reported in the literature.

What characterizes the automatic attentional capture by a perceptual object? The picture that emerges from the present results is that (a) this automatic capture of attention involves a spatial component, (b) the Gestalt factors of collinearity (good continuation) and closure, but apparently not symmetry, suffice for this attentional capture to occur, and (c) the strength of perceptual organization influences this attentional capture.

The finding that the object effect – faster responses for a target that appeared within the object than outside the object – was observed also when the target appeared after the object

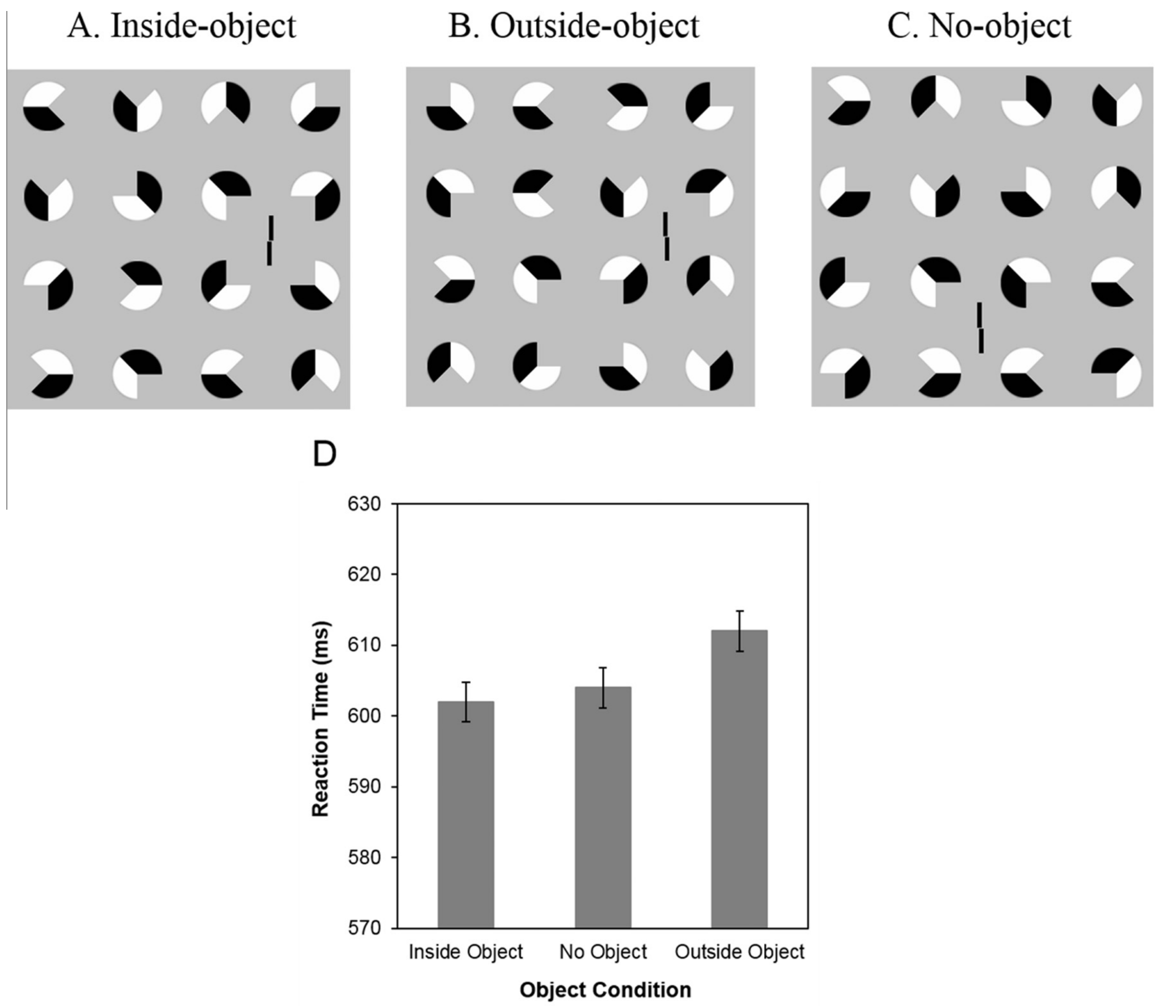

Fig. 11. Examples of the displays in the three conditions of Experiment 3d. (A) Inside-object condition. (B) Outside-object condition. Contrast polarity varies within each local pacman and between spatially separate pacmen inducing the illusory object, including between spatially separated collinear segments. (C) No-object condition. Results for experiment 3d: (D) mean correct RTs as a function of object condition. Error bars represent within subjects ± SEM.

disappeared (Experiment 1b), along with the finding that the object effect was sensitive to spatial manipulations, such that the cost accruing when the target appeared outside the object increased the farther the target was from the object (Experiments 1a - 1b), clearly suggest the involvement of spatial factors. Presumably, the automatic capture of attention by the object, driven by perceptual organization, activates, or is accompanied by deployment of attention to, the spatial locations occupied by the object, consistent with the view that object-related and space-related attentional processing can operate simultaneously and influence one another (e.g., Humphreys & Riddoch, 2003; Mozer & Vecera, 2005).

An object grouped by collinearity, closure, and symmetry combined, an object grouped by closure combined with symmetry, and an object grouped by collinearity alone, each attracted attention automatically, as indicated by the significant, and of similar magnitude, object effect observed for each of these conditions (Experiments 2a–2c). In contrast, no object effect whatsoever was observed for an object grouped by symmetry alone, indicating that no attentional capture occurred (Experiment 2d). These findings suggest that organization by collinearity alone, or by closure (combined with symmetry), suffices for automatic capture of attention by a perceptual object, whereas organization by symmetry alone may not.

As noted earlier (see discussion, Study 2), the suggestion regarding the role of symmetry needs to be taken with caution because the experiment concerning symmetry (Experiment 2d) is not decisive, due to the possibility of confound with proximity in the stimuli.[4] It should also be noted that there is collinearity, in the strict geometrical sense, in our symmetry object (see Fig. 6), which could provide a potential alternative account for an object effect, were such an effect observed. In light of the absence of an object effect with the symmetry object, this is not an issue in the present study, but it should be controlled for, as should proximity, when designing symmetry object in future attempts to understand the role of symmetry in capture of attention.

While being cautious in our claim about the role of symmetry, we note that our findings seem compatible with previous findings demonstrating the important role of collinearity and closure in perceptual organization (e.g., Elder & Zucker, 1993; Field et al., 1993; Mathes & Fahle, 2007), while raising serious concern as whether symmetry plays an important role in perceptual organization (e.g., Devinck & Spillmann, 2013; Hulleman & Humphreys,

[4] A possible way to keep symmetry while controlling for proximity is to use the arrays of pacmen employed in Experiment 3a (Fig. 8), and rotate the four pacmen that form a Kanizsa square by 180° each, such that the opening of each pacman is facing way from the center of the object, yielding an object organized by symmetry. Twelve observers participated in an experiment similar to Experiment 3a, but with the latter symmetry object. The results were similar to those of Experiment 2d, showing no object effects, further suggesting that an object grouped by symmetry alone does not capture attention (even when proximity is controlled for).

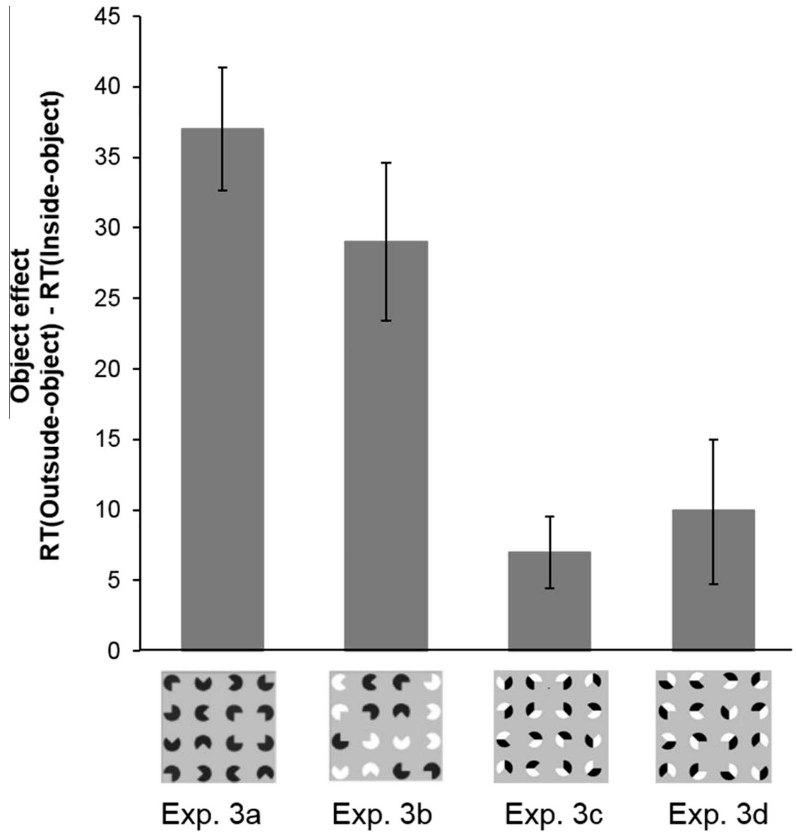

Fig. 12. Object effect [RT(Outside-object) – RT(Inside-object)] in Experiments 3a, 3b, 3c, and 3d. The object effect in Experiments 3a and 3b was significant, and significantly larger than the one in Experiments 3c and 3d. Error bars represent ± SEM.

2004b; Pomerantz & Portillo, 2011). Even when findings suggest some role for symmetry in perceptual organization, it has been claimed that symmetry only comes into play in interaction with other grouping cues that precede the symmetry grouping (e.g., Machilsen et al., 2009). Thus, although human observers are very sensitive to symmetry (e.g., Baylis & Driver, 1995), and symmetry (particularly mirror symmetry) is frequently a salient aspect of perceived form, and plays an important role in figural goodness (Palmer, 1991), the role of symmetry in grouping and segmentation appears to be questionable.

A notable exception is the study of Feldman (2007), which suggests that symmetry does act as a grouping cue. Feldman showed that both collinearity and mirror symmetry induce strong grouping over the course of the first few hundred milliseconds of visual processing. Specifically, comparison of features lying on pairs of line segments was significantly faster if the segments were collinear or were mirror symmetric, suggesting a fast grouping of the segments based upon these cues. Feldman's (2007) finding concerning symmetry is clearly inconsistent with the present finding. However, in Feldman's study, unlike in the present experiments, the display included considerably less elements – just two grouped line segments (the grouped object) and a third line (a foil), and observers were explicitly directed to the grouped object and attended it in order to perform the task. Possibly, symmetry cannot capture attention, but once attended, its effect on grouping surfaces. This suggestion is supported by a recent finding that figure-ground organization was not achieved under inattention when the figural cue was symmetry (Rashal, Kimchi, & Yeshurun, in preparation).

The finding that an object grouped based on collinearity or on closure (combined with symmetry) captures attention in a purely stimulus-driven manner suggests that the Gestalt factors of collinearity and closure may play a role in the formation of "objecthood". The potential role of other Gestalt factors (e.g., proximity, connectedness, common fate), as well as clarifying the role of symmetry, requires further research. In addition, the formation of an object may be flexible to a degree; it may change during the microgenesis of the percept, and may even be somewhat modulated by task requirements. The automatic attentional capture by a perceptual object may serve as a diagnostic test for the formation of "objecthood".

Assuming that the automatic attentional capture by a perceptual object is driven by perceptual organization, the strength of organization is likely to affect this attentional capture. The influence of the strength of perceptual organization on the automatic attentional capture was examined in the context of modal completion. We found that the strength of grouping in modal completion, manipulated by the distribution of contrast polarity reversals within the induced object (e.g., Spehar, 2000), affected the ability of the illusory object to capture attention. Weakening the grouping (i.e., when the reversals in contrast polarity coincided with changes in edge orientation; Experiments 3c - 3d) yielded object effects significantly smaller in magnitude than the ones observed when grouping was strong (Experiments 3a - 3b), indicating that with weakened grouping the ability of the object to capture attention also weakens.

Finally, the present findings converge with a growing body of research, both psychophysical (e.g., Driver et al., 2001; Scholl, 2001) and neurophysiological (e.g., Roelfsema, Lamme, & Spekreijse, 1998; Wannig, Stanisor, & Roelfsema, 2011), suggesting that perceptual organization influences the automatic deployment of attention, such that attention is not only attracted to salient simple features, as assumed by many models of attention (e.g., Itti & Koch, 2000; Koch & Ullman, 1985; Treisman, 1998), but the attraction of attention depends on the segmentation of the visual scene into perceptual objects. A computational model of object based visual salience has been recently proposed (Russell, Mihalas, von der Heydt, Niebur, & Etienne-Cummings, 2014; see also, Mihalas, Dong, von der Heydt, & Niebur, 2011), which successfully accounts for automatic deployment of attention to a perceptual object in an elements display.

Granted that our environment is usually populated by several objects, the deployment of attention may depend on the "strength of objecthood" and on the goals of the observer. This issue awaits further research.

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