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OBSERVATION

Perceptual Grouping Allows for Attention To Cover Noncontiguous Locations and Suppress Capture From Nearby Locations

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A salient stimulus may interrupt visual search because of attentional capture. It has been shown that attentional capture occurs with a wide, but not with a small attentional window. We tested the hypothesis that capture depends more strongly on the shape of the attentional window than on its size. Search elements were arranged in two nested rings. The ring containing the search target remained fixed, while a salient color singleton occurred either in the same or in the other ring. We observed that color singletons only disrupted search when shown in the same ring as the search target. It is important to note that, when focusing on the outer array, which presumably required a larger attentional window, singletons on the inner array did not capture attention. In contrast to the original attentional window hypothesis, our results show that attentional capture does not always occur with a large attentional window. Rather, attention can be flexibly allocated to the set of relevant stimulus locations and attentional capture is confined to the attended locations. Further experiments showed that attention was allocated to search elements that were perceptually grouped into "whole" or "Gestalt"-like objects, which prevented attentional capture from nearby locations. However, when attention was allocated to noncontiguous locations that did not form a perceptual Gestalt, nearby locations elicited attentional capture. Perceptual grouping could be based on a combination of color and position, but not on color alone. Thus, the allocation of attention to Gestalt-like objects that were jointly defined by similarity and proximity prevented attentional capture from nearby locations.

Keywords: attentional window, attentional capture, top-down control, bottom-up control, perceptual grouping

Visual attention selects parts of the available information for further processing. The selected information is prioritized and enters capacity-limited channels like visual short-term memory or consciousness, while nonselected information is likely to go unnoticed. A fundamental and hotly debated question is whether and how attentional selection is driven by bottom-up (Theeuwes, 2010) and top-down factors (e.g., Ansorge, Horstmann, & Scharlau, 2010; Egeth, Leonard, & Leber, 2010; Folk & Remington, 2010; H. J. Müller et al., 2010). To answer this question, variants of Theeuwes' (1991a, 1992) additional singleton paradigm are frequently used. For instance, observers are asked to search for a shape singleton. On some trials, an additional, irrelevant color singleton is presented which slows down search time. Because the disruption increases with the saliency of the irrelevant singleton, Theeuwes (2010) concluded that bottom-up factors drive attention, at least initially (Van Zoest, Donk, & Theeuwes, 2004).

However, attentional capture has been shown to occur only when attention is widely spread across the display. In difficult searches, the attentional window is narrowed to perform a one-by-one inspection of display elements so that salient distractors no longer capture attention (Theeuwes, 2004). Also, a secondary task at central fixation may lead to a small attentional window (Belopolsky & Theeuwes, 2010; Belopolsky, Zwaan, Theeuwes, & Kramer, 2007; Hernández, Costa, & Humphreys, 2010; Yeh & Liao, 2010). For instance, observers attended either the center of the display (focused attention) or the global shape of the search display (spread attention) to decide whether to report the identity of the search target (Belopolsky & Theeuwes, 2010). Despite equal stimulus conditions, attentional capture by a salient color singleton only occurred when attention was spread across the display.

The studies of Belopolsky and Theeuwes (2010) and Belopolsky et al. (2007) have compared two broad attentional states, attention at fixation and attention spread across the display. In natural search, however, observers often look for something in restricted, sometimes noncontiguous regions of space. For instance, we sometimes look for a friend in a group of people by focusing on people sharing the friend's hair color or direction of motion, instead of searching the entire crowd. That is, we only attend to some of the available objects—an idea that is aptly described in the

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guided search model (Wolfe, Cave, & Franzel, 1989). The question pursued in this study is whether attentional capture would only occur if the salient distractor appeared within the attended set of stimuli.

By comparing conditions with valid and invalid cues, previous studies have already shown that attention can be allocated to noncontiguous locations. For instance, Awh and Pashler (2000) presented two cues at noncontiguous locations. The cues informed participants about the most likely locations of the targets and resulted in better perceptual accuracy at the cued than at the intervening locations (see also Hahn & Kramer, 1998). These results speak against the idea of a unitary spotlight of attention that is allocated to contiguous regions of space (e.g., Eriksen & Yeh, 1985; Posner, Snyder, & Davidson, 1980). However, although previous studies have confirmed behavioral and neural signatures of split attention by comparing performance to *relevant* stimuli at validly and invalidly cued locations, there is no research on how attentional capture by *irrelevant* but salient stimuli is modulated by the allocation of attention to noncontiguous locations. Further, there is evidence that the spotlight of attention may take the shape of a ring. For instance, Juola, Bouwhuis, Cooper, and Warner (1991) presented letters at three different eccentricities around the fovea and provided a verbal cue about the upcoming target eccentricity. Reaction times (RTs) were faster with valid than with invalid cues about target eccentricity (see also Cheal & Lyon, 1989). Further, the idea of a ring-shaped focus of attention has been supported by studies measuring evoked potentials (Eimer, 1999; M. M. Müller & Hübner, 2002). To our knowledge, the influence of the shape of the attentional focus on attentional capture has not yet been examined either.

As outlined above, the attentional window hypothesis restricts attentional capture to conditions in which the distribution of attention is broad. But what exactly does "broad" mean? We propose two different readings of broad. According to one interpretation, attention may have to be widely distributed across all objects in the visual field for capture to occur, regardless of whether they are response-relevant or not. In this case, even stimuli that appear at response-irrelevant locations capture attention as long as the focus is wide. According to another interpretation, salient objects only capture attention if they are presented at response-relevant and therefore attended locations. That is, the shape and location of the attentional window is more important than its width.

To test these different readings, we limited the possible target locations to a subset of all possible locations. We presented two nested rings of stimuli and in a block of trials, the target only appeared in one of them (see Figure 1A). Thereby, we created a set of attended and a set of unattended locations. In half of the trials, an additional color singleton was shown either in the attended or in the unattended ring. Because the color singleton was to be ignored, it is also referred to as distractor. The question is whether attentional capture would only occur if the distractor appeared in the attended set or whether it would occur whenever the set of response-relevant locations was widely spread. The condition with targets in the outer ring is crucial for a test between the two interpretations of the attentional window hypothesis: If attentional capture depended on a wide focus of attention, distractors in the inner and outer rings should capture attention because presentation of the target in the outer ring induces a wide attentional window. In contrast, if attentional capture depended on the allocation of attention to the set of stimuli in which the distractor appears, only distractors in the outer ring should capture attention, whereas distractors in the inner ring are ineffective. The condition with targets in the inner ring does not discriminate between the two accounts: Distractors in the outer array should not capture attention both because the attentional window is small and because the outer ring is not attended.

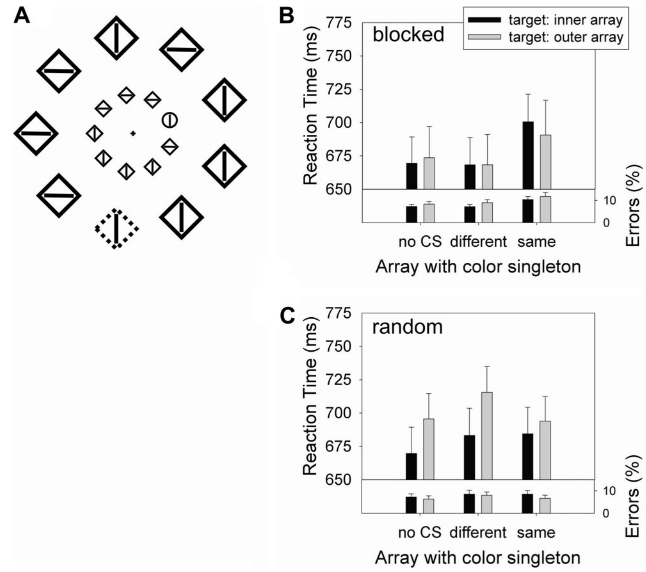

Figure 1. Stimuli (approximately drawn to scale) and results in Experiments 1 and 2. Panel A shows the inner and outer ring of stimuli. Subjects looked for a fixed-shape singleton (here: circle) and reported the orientation of the line inside. A color distractor (here: indicated by a dotted line) could be present in the inner or outer ring. Panels B and C show mean reaction times and error percentages when the ring containing the target remained the same in a block of trials or varied randomly, respectively. Error bars denote the between-subject standard error. No CS = no color singleton.

Further, we investigated the possible shapes of the attentional window. Our working hypothesis is that the shape of the attentional window is determined by perceptual grouping of the stimulus elements because there were nine elements in our search displays and we know of no study showing that there can be up to nine independent foci of attention. Most studies reporting evidence for split attention (with static stimuli) have used only two noncontiguous locations (e.g., Awh & Pashler, 2000; Hahn & Kramer, 1998; M. M. Müller, Malinowski, Gruber, & Hillyard, 2003), unless they investigated a "whole" or "Gestalt"-like distribution, such as a ring (Cheal & Lyon, 1989; Eimer, 1999; M. M. Müller & Hübner, 2002). Therefore, we think that it may be impossible to shape the attentional window to a large number of random locations that do not form a unitary perceptual Gestalt.

Experiment 1: Blocked Target Rings

Method

Participants. Sixteen undergraduate psychology students at the University of Geneva participated for course credit. The procedure was approved by the local ethics committee.

Stimuli. Stimuli were generated using the Cogent Toolbox for Matlab (Laboratory of Neurobiology, UCL, London, UK) and presented on a 21" CRT with 1280 × 1024 pixels. Head movements were restrained at 66 cm from the screen by a chin rest. A white, 0.5° fixation cross was presented in the center of the black background with a luminance of 0.3 cd/m^2. Nine elements were arranged in the inner ring at 4° of eccentricity and another nine in the outer ring at 10° of eccentricity. In the inner ring, the stimulus diameter was 1.5° for the circle and 1.7° for the diamond. The length of the vertical or horizontal lines inside the shapes was 1.2°. In the outer ring, stimuli were magnified by a factor of 2.5 to compensate for the lower spatial resolution in the periphery. In particular, the adjustment of stimulus size was intended to prevent differences in RT between the inner and outer ring. Additionally, line width was 0.125° in the outer ring instead of 0.025° in the inner ring. The outline shapes (circle or diamond) were presented in either green or red and the line stimuli were gray. All stimuli had a luminance of ~22.5 cd/m^2. The search display was shown for 203 ms.

Procedure. Participants' task was to indicate the orientation of the line inside the shape singleton by pressing the left or right arrow key on a standard computer keyboard. The shape singleton was either a diamond among circles or a circle among diamonds. It was fixed for each participant. The stimulus color changed unpredictably from trial to trial. On 50% of the trials, there was no color singleton. On 25% of trials, the color singleton was presented in the inner ring and on the remaining 25% of trials it was in the outer ring. In a block of trials, the target's eccentricity was fixed, whereas the eccentricity and presence of the color singleton changed randomly. The target ring switched between blocks. Participants completed one practice block of 128 trials for each target ring and then worked through four experimental blocks of 128 trials. Each block started with 12 warm-up trials that were not recorded. Block order, response assignment, and shape singleton were counterbalanced across participants. Participants were instructed to respond as rapidly as possible without making too many errors. Performance feedback was given every 64 trials and participants were told to keep the error rate below 10%. Visual feedback was given after choice errors, anticipations (RT shorter than 100 ms), and late trials (RT longer than 1200 ms).

Results

Anticipations were highly infrequent in this and the remaining experiments (far less than 1%) and will not be reported separately. Anticipations and late trials (1%) were excluded from analysis. The overall percentage of errors was 10% and somewhat higher than expected on the basis of the instruction. Proportion correct and mean RTs were calculated for each condition and participant. A summary of RTs, sample sizes, late trials, and overall error rates for all experiments is shown in Table 1. Mean RTs and choice error rates for this experiment are shown in Figure 1B.

Reaction times. A within-subject, 2 (target ring: inner, outer) × 3 (distractor ring: absent, different ring, same ring) ANOVA was run on mean RTs of correct trials. The main effect of distractor ring, $F(2, 30) = 16.08$, $p < .001$, showed that RTs were longer with color singletons in the same ring as the target (696 ms) than with color singletons in the other ring (668 ms) or no color singletons (672 ms). Planned *t* tests (cf. Table 1) confirmed that RTs increased with distractors in the same ring compared with the no-distractor condition, $t(15) = 4.14$, $p = .001$, but not with distractors in the other ring, $p = .433$. The main effect of target ring was not significant, $p = .855$, showing that RTs were equal to targets in the inner and outer ring, which we had hoped to achieve by enlarging the stimuli. Also, there was no interaction, $p = .213$.

Choice errors. A second two-way ANOVA on the percentage of choice errors showed that more errors occurred when the distractor appeared in the target ring (11%) than when it appeared in the other ring (8%) or when no distractor was present (7%), $F(2, 30) = 7.91$, $p = .002$. No other effects were significant.

Intertrial effects. We evaluated whether intertrial effects may account for the results. It has been shown that presentation of the target on a position occupied by a distractor in the previous trial resulted in slow RTs (Kumada & Humphreys, 2002; Maljkovic & Nakayama, 1996). Conversely, presenting the target on the previous target's position accelerated RTs. Although not explicitly analyzed in these studies, a distractor presented at the target position of the preceding trial may cause larger interference than when it was presented elsewhere. In Table 2, we present the different transitions between the preceding and the current trial. There was an imbalance between color singletons presented on the

Table 1
Results From Experiments 1–6

	Distractor array					
	No CS	Different	Same	*N*	Error rate	Late trials
Exp. 1 blocked	672	−3	24**	16	10%	1%
Exp. 2 random	683	17**	7#	15	8%	1%
Exp. 3 single array	717	21*	33*	15	7%	3%
Exp. 4 feature/position	681	2	13**	19	10%	2%
Exp. 5 position	705	18**	22**	18	9%	1%
Exp. 6 feature	705	1	3	16	9%	1%

Note. Mean reaction times (RTs) without color singleton (in ms) and the change in RT when a color distractor was shown on the same ring/array as the target or on a different ring/array. The overall error rate (anticipations, late trials, choice errors) and late trials are listed. Choice errors are analyzed separately.
The symbols #, *, and ** correspond to $p < .06$, .025, and .01, respectively. No CS = no color singleton.

Table 2
Inter-Trial Transitions on the Same Position

Same position		Current distractor in	
Previous	Current	Same ring	Other ring
Distractor	Target	Yes	Yes
Target	Target	Yes	Yes
Distractor	Distractor	Yes	Yes
Target	Distractor	Yes	No

Note. In the first two columns, transitions between distractor and target on previous and current trials are listed. For instance, the first case shows that the target in the current trial appeared on the same position as the distractor in the previous trial. The third and fourth columns indicate whether a transition was possible in the two main experimental conditions. When the current distractor appeared in the same ring as the target, all transitions were possible. When the current distractor appeared in the other ring, it was not possible that the distractor on the current trial was in the same position as the target in the previous trial because target eccentricity was fixed in a trial of blocks.

same ring as the target and those presented on a different ring: Color singletons could only occupy the previous target position when the color singleton in the current trial was presented in the same ring as the target. As target eccentricity was fixed in one block, the distractor could never occupy the previous target location and occur in the other ring at the same time. This imbalance could explain the RT differences. On average, the distractor appeared in 15 out of 128 trials on the previous position of the target.

We reran the above analysis of RTs after excluding the relevant successive location overlap trials from the condition with distractors in the same ring as the target. The results were essentially unchanged: The main effect of distractor ring, $F(2, 30) = 12.68$, $p < .001$, was replicated. Planned t tests confirmed that RTs increased with distractors in the same ring compared with the no-distractor condition (692 vs. 672 ms), $t(15) = 3.72$, $p = .002$. Therefore, intertrial effects cannot account for the results.

Discussion

We observed that color singletons appearing in the attended ring resulted in larger attentional capture than color singletons that appeared in the unattended ring. For instance, when the target occurred in the outer ring, distractors in the outer ring resulted in attentional capture, whereas color singletons in the inner ring did not. These results are incompatible with the initial version of the attentional window hypothesis, which predicts that salient distractors in both rings should attract attention, as presenting the target consistently in the outer ring should have resulted in a large attentional window encompassing the inner ring.

To counter our conclusions, one may argue that attention to the large target in the outer ring (2.5 times larger) prevented the smaller color singleton in the inner ring to capture attention. To test this alternative hypothesis, we presented the same stimuli again, but did not block target location. The target appeared randomly in the inner or outer ring such that the width of the attentional window was always large. The critical question is whether small color singletons in the inner ring will capture attention when the target is a large stimulus in the outer ring.

Experiment 2: Random Target Rings

Method

The methods were the same as in Experiment 1, with the following exceptions. The target appeared unpredictably in the inner or outer ring. Twenty students participated, but the data of five was discarded because of error rates larger than 20% (mean of 28% errors, from 25% to 31%). The relatively high number of discarded data sets may be caused by the larger set size of the search array (18 instead of 9) which made the task very difficult for some, but not all participants.

Results

Mean RTs and error rates are shown in Table 1 and Figure 1C. A two-way ANOVA showed that responses were faster for targets in the inner ring than for targets in the outer ring (679 vs. 702 ms), $F(1, 14) = 6.31$, $p = .025$. The effect of distractor ring was significant, $F(2, 28) = 7.6$, $p = .002$. RTs were longer with distractors in the other ring than without distractor (699 vs. 683 ms), $t(14) = 3.2$, $p = .006$, but only marginally longer with distractors in the same ring than without distractor (689 vs. 683 ms), $t(14) = 2.07$, $p = .058$. The interaction of target ring and distractor ring was significant, $F(2, 28) = 4.15$, $p = .026$. For targets in the inner ring, RTs increased by 15 ms with small color singletons in the same ring, $t(14) = 2.47$, $p = .027$, and by 14 ms with large color singletons in the outer ring, $t(14) = 2.89$, $p = .012$. For targets in the outer ring, the small color singleton in the inner ring increased RTs by 20 ms, $t(14) = 2.61$, $p = .021$, whereas the large color singleton in the outer ring did not (2 ms), $p = .729$. The ANOVA on error rates did not yield any significant results, $ps > .106$.

Discussion

The present results are markedly different from the ones observed with the blocked target ring. When the target ring varied randomly, RTs increased not only when the distractor appeared in the same ring as the target, but also when it appeared in the other ring. For targets in the outer ring, there was even a reversal of the results of Experiment 1: No attentional capture with distractors in the same ring, but strong capture with distractors in the other ring. We speculate that at the onset of the display, attention was focused on the inner ring, which caused shorter RTs to targets in the inner ring and resulted in attentional capture by distractors in that ring when the target could not be found there. In any case, the present results rule out the hypothesis that the absence of attentional capture by small color singletons in the inner ring with large targets in the outer ring occurred because of size differences. At least for targets in the inner ring, distraction was similar for small and large color singletons. It is not entirely clear why there was no distraction from the large singletons when targets were in the outer ring, but the important point is that small color singletons in the inner ring resulted in strong distraction, even with large targets on the outer ring. These results are incompatible with the idea that small color singletons close to the fovea distract less than large color singletons further away.

Experiment 3: Single Ring

As laid out in the introduction, there is evidence that attention may be split between noncontiguous locations. Often, this implied two attended locations (Awh & Pashler, 2000; Hahn & Kramer, 1998), whereas we had nine different locations. The objects in those locations were grouped to form a ring which may be considered a perceptual Gestalt. The question arises whether attention was allocated to noncontiguous locations or to the perceptual Gestalt. If the results are due to noncontiguous allocation of attention, target arrays that are not strongly grouped should yield the same difference in attentional capture between attended and nonattended stimulus arrays as target arrays that form a perceptual Gestalt.

Methods

The methods were as in Experiment 1 with the following exceptions. There was only one ring at 4° of eccentricity, with eight stimuli aligned on the vertical, horizontal, and diagonal axes. The form singleton containing the target line was fixed for each participant and counterbalanced across participants. The target appeared on only four out of the eight possible positions. For half of the observers, the target array was on the cardinal axes (above, below, left, right). For the other half, the target array was on the diagonals (upper left, upper right, lower left, lower right). The target array was indicated by the characters "+" and "×" at central fixation (line length of 1°). Participants were instructed to focus on the potential target positions.

Results

Mean RTs and error rates are shown in Table 1 and Figure 2B. A within-subject, one-way (distractor array: absent, different array, same array) ANOVA on RTs revealed a significant main effect of distractor array, $F(2, 26) = 19.27$, $p < .001$. RTs were slower with color singletons in the same array compared with the distractor-absent condition (750 vs. 717 ms), $t(14) = 6.38$, $p < .001$. However, presentation of color singletons in a different array also increased RTs (738 vs. 717 ms), $t(14) = 2.89$, $p = .012$, although significantly less than the distractors in the same array (750 vs. 738 ms), $t(14) = 2.76$, $p = .015$. A second ANOVA on percentage of choice errors did not reveal any significant effects, $ps > .693$.

Next, we identified trials in which the distractor appeared on the previous target position, as this transition is unique to the same-array condition. On average, 19 trials per participant were concerned, which amounts to 24% of 80 trials in this condition. After exclusion of these trials, RTs in the condition with distractors on the target array dropped from 750 to 741 ms. Though the main effect of condition in the ANOVA was still significant, $F(2, 26) = 11.95$, $p < .001$, the difference between color singletons on same and different arrays disappeared (741 vs. 738, $p = .453$).

Discussion

Attentional capture occurred with color singletons on positions the target never occupied, suggesting that the attentional window could not be adjusted to noncontiguous positions that were not strongly grouped. With respect to Experiment 1, we conclude that attention was not allocated to noncontiguous spatial locations, but to the perceptual Gestalt created by placing objects on a circle, resulting in a perceived ring. Nonetheless, a possible alternative explanation for the discrepancy between Experiments 1 and 3 is that the distance between the target array and the remaining elements was smaller in Experiment 3 (center-to-center distance of 3.1°) than with the nested arrays in Experiment 1 (distance of 6°). Because the distance was smaller, the nonattended locations may have been too close to permit exclusion from the focus of attention. Among other things, Experiment 4 addresses this issue.

Experiment 4: Grouping by Feature and Position

Some of the Gestalt laws involve relative object position and others involve object features (e.g., Spillmann, 2009; Wagemans, Wichmann, & Op de Beeck, 2005). In Experiments 1 and 2, the law of proximity and the law of similarity (with respect to object size) resulted in the perception of two rings. To tease apart contributions of location-based and feature-based grouping, we created a new circular stimulus that was not perceived as two nested rings in the absence of featural differences. However, when a feature contrast was added, the perception of an inner and outer

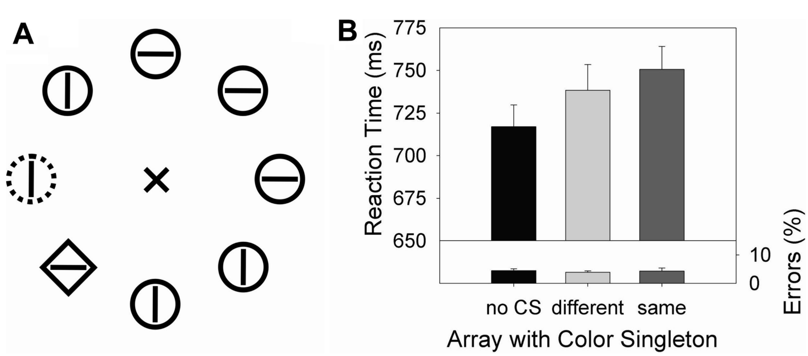

Figure 2. Stimuli (approximately drawn to scale, Panel A) and results (Panel B) in Experiment 3. The target shape singleton could be presented either on the cardinal axes or on the diagonals (varied across observers and additionally emphasized by the fixation mark which was either a "+" or a "×"). Color singleton distractors could occur at any position, thus being either on the same or different array as the target. Error bars denote the between-subject standard error. No CS = no color singleton.

ring emerged. To this end, we reduced the difference in eccentricity between the inner and outer rings to 1° and removed the difference in size. Without feature contrast, the two rings were not consistently grouped, but rather perceived as an irregular circle (see Figure 3C). When the inner ring had a different color than the outer (see Figure 3A), two rings were clearly perceived, despite the small difference in eccentricity. Subjectively, the grouping was stronger for the inner than for the outer array, possibly due to the smaller distance between the elements. Essentially, Experiment 4 is a replication of Experiment 1 with the exception that location-based grouping was not sufficient to yield the perception of two rings. To group the objects, we presented stimuli on the inner and outer circle in different colors. In a block of trials, a set of dark or bright colors was assigned to the inner or outer rings.

Method

The methods were as in Experiment 1 with the following exceptions. Inner and outer ring had eccentricities of 4° and 5°, respectively, which resulted in a distance of 1.8° between adjacent stimuli. To increase the visibility of the color, line width was set to 0.125° for the outline shapes. Line width was 0.025° for the vertical or horizontal lines inside the shapes. There were two sets of colors. The dark set comprised green and red (both 4 cd/m^2), whereas the bright set comprised yellow and magenta (both 78 cd/m^2). For a block of 128 trials, the dark set was assigned to the inner ring and the bright set to the outer ring, or vice versa. Between blocks, the assignment changed such that each color set occurred on each ring twice (once containing the target). The order of the four combinations of color set and target ring was counterbalanced across participants. The color of the target and distractor ring varied randomly from trial to trial within the assigned set. For instance, if the dark set was assigned to the inner ring, the stimuli on the inner ring could be red, and stimuli on the outer ring could be yellow. In this case, a distractor on the inner ring would be green, and a distractor on the outer ring would be magenta. Before each block, participants were instructed to look for a particular target shape in a specific ring (inner or outer) and color set (dark: red and green, or bright: yellow and magenta). Twenty students participated, but the data from one had to be discarded due to an error rate of 39%.

Results

Mean RTs and error rates are shown in Table 1 and Figure 3B. A within-subject, two-way ANOVA was run on RTs. RTs were faster with targets on the inner compared with the outer ring (680 vs. 692 ms), $F(1, 18) = 4.92$, $p = .04$. The main effect of distractor ring, $F(2, 36) = 9.99$, $p < .001$, showed that RTs were slower with distractors in the same ring compared with the condition without distractors (693 vs. 681 ms), $t(18) = 3.56$, $p = .002$. In contrast, distractors in a different ring did not prolong RTs (683 vs. 681), $p = .416$. Although Figure 3B suggests that the effect of distractor ring was larger for the inner than the outer ring, the interaction was far from significant, $p = .444$. A second ANOVA on the percentage of choice errors showed that more errors occurred when the distractor appeared on the target ring (9%) or the other ring (9%) than when no distractor was present (7%), $F(2, 36) = 4.1$, $p = .025$. No other effect was significant, $p > .375$.

Controlling for intertrial effects (see Experiment 1) did not change the pattern of results: After exclusion of the relevant successive location overlap trials, the main effects of target ring, $F(2, 36) = 4.71$, $p = .044$, and distractor ring, $F(2, 36) = 6.41$, $p = .004$, on RTs were replicated. A planned *t* test confirmed that RTs were slower with distractors in the same ring compared with the condition without distractors (691 vs. 681 ms), $t(18) = 2.93$, $p = .009$.

Discussion

The results show that the allocation of attention to a Gestalt that results jointly from feature and location contrast prevents attentional capture by singletons on a nonattended ring. The final two experiments will show whether grouping by position or grouping by feature alone can account for these findings. To this end, the feature contrast between inner and outer ring was removed in Experiment 5, and the difference in eccentricity was removed in Experiment 6. The question is whether the remaining, presumably weak grouping cues are sufficient to allow for the suppression of attentional capture from nearby locations.

Experiment 5: Grouping by Position

To examine whether the spatial configuration allowed for object grouping, we removed the color/luminance difference between the inner and outer ring.

Method

The methods were as in Experiment 4 with the following exceptions. The inner and outer ring had the same color. In a block of 128 trials, the color was randomly drawn from one of the two color sets. Besides color set, target ring was blocked. Before each block, participants were instructed to attend to the upcoming target ring (inner or outer), even though the grouping by position was not very salient (cf. Figure 3C). Eighteen students participated.

Results

Mean RTs and error rates are shown in Table 1 and Figure 3D. A within-subject, two-way ANOVA was run on RTs. The main effect of color singleton ring, $F(2, 32) = 20.55$, $p < .001$, showed that RTs were slower with distractors in the same ring as the target, compared with trials without distractors (726 vs. 705 ms), $t(16) = 6.03$, $p < .001$. Similarly, distractors in a different ring prolonged RTs (722 vs. 705), $t(16) = 5.97$, $p < .001$. The interaction of target ring and distractor ring, $F(2, 32) = 6.32$, $p = .005$, showed that the increase in RT observed when the color distractor was in a different ring was mostly driven by the targets in the outer ring (cf. Figure 3D). As in Experiment 2, distractors in the inner ring caused strong interference when the target was in the outer ring. A second ANOVA on the percentage of choice errors did not yield any significant effects, *p*s $> .137$.

Experiment 6: Grouping by Color

Finally, we removed spatial grouping cues by placing all elements on the same circle while keeping the same features as in Experiment 4.

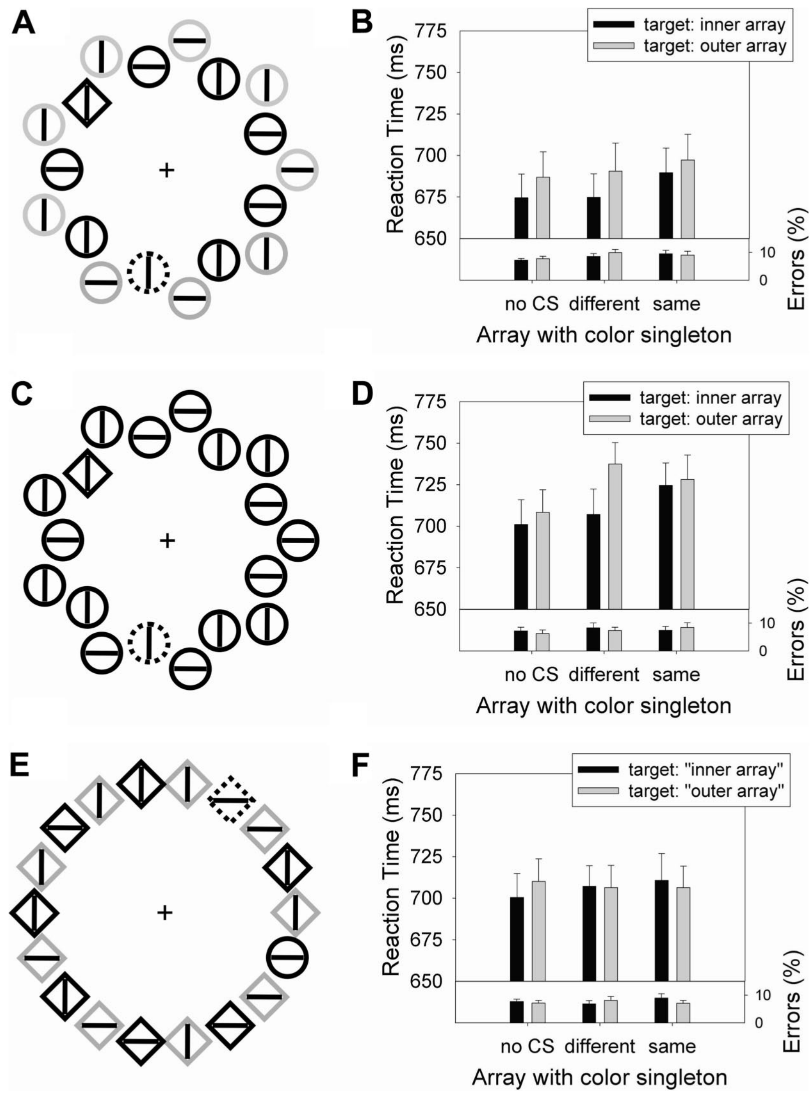

Figure 3. Stimuli (approximately drawn to scale) and results. The top, middle, and bottom rows correspond to Experiments 4, 5, and 6, respectively. In all sample displays, target and distractor are in the inner ring. In Experiment 6, the ring anchored on the 3 o'clock position is referred to as the "outer ring" for comparison with the previous experiments. Error bars denote the between-subject standard error. No CS = no color singleton.

Method

The methods were as in Experiment 4 with the following exceptions. The inner and outer ring had the same eccentricity of 5°, which resulted in a distance of 1.7° between adjacent stimuli. In principle, they could still be distinguished on the basis of position, because the former outer ring was anchored on the 3 o'clock position (cf. Figure 3E). However, grouping by position was essentially absent because there were too many stimuli (18) on a single circle. Before each block, participants were instructed to attend to the upcoming color set of the target (dark: red and green, or bright: yellow and magenta). Eighteen students participated, but the data from two participants was discarded due to high error rates (22% and 35%).

Results

Mean RTs and error rates are shown in Table 1 and Figure 3F. A within-subject, two-way ANOVA was run on RTs. The interaction of target ring and distractor approached significance, $F(2, 30) = 3.01$, $p = .064$. No other effect was significant, *p*s $> .731$. A second ANOVA on the percentage of choice errors did not yield any significant effects, *p*s $> .178$.

Discussion

When spatial grouping cues were removed, but the same features were presented as in Experiment 4, no attentional capture was observed. Perceptually, the display appeared cluttered, as different colors and elements of the same color did not group. Therefore, the additional color singleton did not pop out. Taken together, Experiments 5 and 6 suggest that only the combination of feature and location cues allow for the successful allocation of attention to the perceptual Gestalt in Experiment 4. Perceptual grouping resulting from location or feature contrast alone was not possible.

General Discussion

We investigated how the size and shape of the attentional window affects attentional capture. In previous studies, two broad attentional states have been distinguished: attention at central fixation and attention spread across the display elements (Belopolsky & Theeuwes, 2010; Belopolsky et al., 2007). Here, we refined the notion of a broad attentional window by presenting various configurations of response-relevant and response-irrelevant locations. The hypothesis was that attention would be flexibly allocated to response-relevant locations, thereby preventing attentional capture from nonattended locations. In Experiments 1 and 4, response-relevant and -irrelevant locations were grouped by the laws of proximity and similarity into rings. We observed that capture only occurred when the salient color singleton occurred in the attended ring. It was not the case that a wide spread of the relevant stimuli (i.e., target in outer ring) caused ubiquitous attentional capture in the entire region encompassed by the stimuli. Thus, it is not the size of the attentional window per se that determines attentional capture, but the shape of the attentional window which results from flexibly allocating attention to task-relevant stimuli. For the present stimuli, the shape of the attentional focus departed from the classical zoom-lens model and followed the shape of a ring which was perceived as a “whole” or “Gestalt” because of perceptual grouping. Experiment 4 showed that perceptual grouping could be jointly based on the proximity of stimulus elements and their similarities. Neither proximity alone (Experiment 5) nor similarity alone (Experiment 6) was sufficient to explain the results. Further, the present experiments do not support the idea that attention was allocated to noncontiguous locations independently of perceptual grouping. In Experiment 3, four out of eight locations in a ring were response-relevant, but this did not prevent attentional capture by stimuli in the response-irrelevant locations.

In sum, we think that attention was not allocated to independent locations as in studies on split attention, but to configurations resulting from perceptual grouping. Therefore, our results are related to studies showing that attention can be allocated to objects (Egly, Driver, & Rafal, 1994; Moore, Yantis, & Vaughan, 1998). In the present case, the “object” was composed of multiple subunits that formed a perceptual Gestalt. Despite the differences between the geometric objects used in studies on object-based attention and our ring-like configurations, there may be more similarities than differences. The process of perceptual grouping that occurs when the stimuli form a ring may be very similar to the process of figure-ground segregation that occurs when we perceive an object. In both cases, preattentive grouping processes may be at play (e.g., Marr, 1982).

The idea that the allocation of attention is based on perceptual grouping received support from a recent study with apparent motion stimuli. Boi, Vergeer, Ogmen, and Herzog (2011) presented a search display framed by a square that moved in abrupt steps from left to right. Surprisingly, cues presented in the search display induced attentional enhancement with respect to the same position in the square, even when the entire search square had been displaced. Thus, an object-centered reference frame that was defined by perceptual grouping relations may act as the basis for the deployment of attention. Also, it has been observed that distraction from irrelevant elements next to the response-relevant location in the Eriksen flanker task and the attentional blink paradigm are stronger if those elements perceptually group with the target (Baylis & Driver, 1992; Folk, Leber, & Egeth, 2002).

Further, the lack of attentional capture from singletons on the nonattended ring is consistent with studies showing that abrupt onsets typically attract attention, but can be ignored if attention was focused at the location indicated by a 100% valid cue (Theeuwes, 1991b; Yantis & Johnston, 1990). With cues that were only partially valid, however, abrupt onsets slowed down performance. Similar to our study, distracting events could only be ignored when they occurred in locations that were never attended. If the locations are response-relevant, attentional capture reemerged: In Experiment 2, targets appeared randomly in either ring such that both had to be attended and attentional capture occurred with distractors on the same and on the other ring.

Finally, the present results suggest that observers were able to adjust their attentional control settings to meet the task requirements. That is, they paid attention only to the relevant stimuli which precluded distraction from singletons elsewhere. In the same vein, it has been observed that attentional capture decreases when the proportion of trials with irrelevant singletons increases (Geyer, Müller, & Krummenacher, 2008; Sayim, Grubert, Herzog, & Krummenacher, 2010; see also Becker, Ansorge, & Horstmann, 2009; Horstmann & Ansorge, 2006). It is a matter of debate whether the reduced attentional capture is a consequence of reduced stimulus uncertainty (Theeuwes, 2010) or whether it is the result of a top-down control strategy to suppress the distractor (Geyer et al., 2008). In the present case, our intertrial analysis suggests that automatic intertrial inhibition processes do not play a major role. Thus, we favor the top-down control of attention, rather than intertrial inhibition, as an explanation. In our view, however, the more important point is that the attentional system responds flexibly to the stimulus conditions, thereby attenuating the impact of distracting elements. Perceptual grouping factors provide the basis for the segregation of the visual array in relevant and irrelevant elements, but the observer flexibly allocates attention to perceptual Gestalts, thereby attenuating distraction from nearby locations.

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