Vision Research 179 (2021) 1–8

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

The size of attentional focus modulates the perception of object location

Wladimir Kirsch *, Wilfried Kunde

Department of Psychology, University of Würzburg, Germany

ARTICLE INFO

Keywords:
Attention
Location perception
Attentional repulsion effect

ABSTRACT

The present study examined how the size of attended area affects the repulsion of perceived object location from the focus of attention reported previously (attentional repulsion effect). We induced sustained changes in the size of attentional focus and tested the impact of this experimental variation on the perception of object location. The results of three experiments revealed reliable repulsion effects for each size of attentional focus. However, the magnitude of the effect decreased substantially with an increase in focus size. This outcome extends the knowledge about how spatial attention affects visual perception.

1. Introduction

Spatial attention affects performance in diverse visual tasks. Notably, attentional processes alter not only the efficiency of object perception but also several characteristics of objects' appearance (see Carrasco & Barbot, 2019, for a review). Such effects have been demonstrated, e.g., for size (Anton-Erxleben, Henrich, & Treue, 2007), shape (Fortenbaugh, Prinzmetal, & Robertson, 2011), contrast (Carrasco, Ling, & Read, 2004) and spatial frequency (Gobell & Carrasco, 2005). The focus of the present study was on the perception of stimulus location, another feature susceptible to attentional influences.

Previous research revealed that perceived stimulus locations shift away from attended locations (Arnott & Goodale, 2006; Baumeler, Nako, Born, & Eimer, 2020; Cutrone, Heeger, & Carrasco, 2018; DiGiacomo & Pratt, 2012; Klein, Paffen, Pas, & Dumoulin, 2016; Kosovicheva, Fortenbaugh, & Robertson, 2010; Pratt & Arnott, 2008; Pratt & Turk-Browne, 2003; Suzuki & Cavanagh, 1997). This "attentional repulsion effect" (ARE) is usually demonstrated using a double-cue paradigm in which participants are asked to judge the horizontal displacement of two vertical lines placed one upon the other (Vernier task). The Vernier task is preceded by a pair of small stimuli (exogenous attentional cues) briefly presented in diagonally opposite quadrants of the display (i.e. in the upper-left and lower-right or in the lower-left and upper-right quadrants). The locations of the Vernier lines are misperceived as being horizontally shifted away from the attentional cues. This distortion has also been reliably observed under endogenous (i.e. voluntary) attention conditions (Baumeler et al., 2020; Cutrone et al., 2018; Suzuki & Cavanagh, 1997).

In the present study, we tested whether and how the ARE is affected by the spread of the attended area, i.e. by the size of attentional focus. This question is important for at least three reasons. First, it is underexplored. There are only two studies to our knowledge, which tackled this issue. Kosovicheva et al. (2010) manipulated the size of exogenous attentional cues (what can be assumed to entail changes in focus size) and observed only little evidence for the impact of this factor on the magnitude of ARE. In a similar vein, Cutrone et al. (2018) did not find any differences between different sizes of attentional field induced by voluntary allocation of attention. We return to this research in Section 2.

Second, and in contrast to these findings, some evidence from related paradigms suggests changes in apparent stimulus location as a function of attentional distribution (Bocianski, Müsseler, & Erlhagen, 2010; Fortenbaugh & Robertson, 2011; Fortenbaugh, Robertson, & Esterman, 2017; Kirsch, Heitling, & Kunde, 2018). For example, briefly presented peripheral stimuli are often mislocalized towards the fovea. This "foveal bias" decreases under conditions of focused attention and increases with distributed attention (Bocianski et al., 2010; Fortenbaugh & Robertson, 2011).

Third, theoretical accounts applied to the ARE and related phenomena explicitly predict differences in perceived stimulus location for differently sized attentional fields. It has been proposed that dynamic features of receptive fields of cortical neurons (RF) are responsible for the perceptual distortions like the ARE (Anton-Erxleben & Carrasco, 2013; Baruch & Yeshurun, 2014; Carrasco & Barbot, 2019; Klein et al., 2016; Suzuki & Cavanagh, 1997). This claim is consistent with neurophysiological evidence for the impact of attention on the properties of RF (Anton-Erxleben, Stephan, & Treue, 2009; Klein, Harvey, &

* Corresponding author at: Institut für Psychologie III der Universität Würzburg, Röntgenring 11, D-97070 Würzburg, Germany.
E-mail address: kirsch@psychologie.uni-wuerzburg.de (W. Kirsch).

https://doi.org/10.1016/j.visres.2020.11.004
Received 21 September 2020; Received in revised form 12 November 2020; Accepted 13 November 2020
Available online 29 November 2020

Dumoulin, 2014; Womelsdorf, Anton-Erxleben, & Treue, 2008), though the link between neurophysiological and behavioral data is not well established yet. In essence, the perceptual repulsion has been explained by a shift of RF towards, and their shrinkage at, the attended location[1]. One consequence of such dynamic cortical changes is that an object like a Vernier line activates neurons with RF originally located further away from the currently attended location.

Importantly, these mechanisms should depend on the size of attentional focus. In particular, the magnitude of the RF shift should decrease, the larger the spatial area that is attended (Baruch & Yeshurun, 2014; Klein et al., 2016). Accordingly, the impact of attention on visual appearance should decrease with an increase in attentional focus. This prediction is consistent with the idea of limited resources implemented in the "zoom-lens" model of attention in which processing efficiency for stimuli within the focus decreases when the focus gets larger (Eriksen & St. James, 1986; see also e.g., Castiello & Umiltà, 1990, and Müller, Bartelt, Donner, Villringer, & Brandt, 2003).

The results of our recent study confirmed this prediction for size perception: when attention was allocated at the center of a circular stimulus, that stimulus was perceived as larger as compared with a neutral attentional condition (Kirsch et al., 2018; see also Anton-Erxleben et al., 2007). This effect, however, disappeared completely and was even reversed when attention was spread over a large spatial area surrounding the target stimulus. This outcome has been ascribed to attentional changes of RF outlined above and thus indicated the existence of similar phenomena in other branches of spatial perception.

Whether such a phenomenon exists in the perception of object location was the primary question of the present study. More precisely, we used a version of the ARE paradigm and tested the hypothesis that the perceptual repulsion from the center of attention decreases with an increase in the size of attentional focus. To anticipate the results, three experiments reported below revealed strong support for this hypothesis.

2. Experiment 1

The methodical approach of the present study is based on the previous research of Kosovicheva et al. (2010) and Cutrone et al. (2018) which did not reveal evidence for the impact of focus size on the ARE as mentioned. A closer look on the experimental protocols and data provided some clues for this null result. Kosovicheva et al. (2010) presented unfilled circles and ovals before the Vernier lines. The location but not the size of these exogenous attentional cues substantially affected the perception of the Vernier stimuli. This result suggested that the center of the cue attracted participants' attention rather than its contour. Thus, it seems that the size variation of the unfilled cues did not effectively induce changes in the size of attentional focus (provided that our main hypothesis is valid; but see "large oval cue" condition of Exp.2 in that study). Cutrone et al. (2018) used an endogenous attentional task to vary the size of attentional field. Participants saw a rapid sequence of letters bevor the Vernier task. Endogenous cues indicated locations at which a target letter will appear in some trials. The size of attentional focus was varied via spatial extent of possible target locations that was either small or large. Somewhat surprisingly, in the large focus condition the target detection task proved to be easier than in the small focus condition. Also, the target letter appeared infrequently (in 20% of trials). It seems thus conceivable that participants did not systematically broaden their focus to perform the detection task in this condition. Moreover, a rather small sample of participants was tested in this study and the magnitude of the attentional field manipulation was rather limited. Thus, a possible effect might have been too small to be detected (see also a descriptive trend in Fig. 3b of that study).

The present study attempted to overcome these limitations. In particular, we used a new version of the ARE paradigm that induced sustained rather than transient attentional changes as in Cutrone et al. (2018; see also Baumeler et al., 2020; Suzuki & Cavanagh, 1997). Similar to the study of Kosovicheva et al. (2010) we included unfilled circles (and ovals in Exp.2 and 3) to vary the location and size of attentional focus. To ensure that participants attended the whole figure (rather than only it center) we forced them to compare the size of the circles. Exp.1 aimed to establish this paradigm. Participants were exposed to a dual-task, in which a size discrimination task and a Vernier line task were performed in a random succession in each block of trials.

In the Vernier task, two lines were presented above and below fixation and the perception of line positions was measured using a method of constant stimuli. In each Vernier trial, participants judged whether the top line was located to the left or to the right compared with the bottom line. The size discrimination task required a comparison of two circles presented in the diagonally opposite quadrants of the display (i.e. at locations of transient cues often used in previous studies) in respect to their size. That is, circles were located either in the upper-right and lower-left or and in the upper-left and lower-right quadrants. The circle locations varied between different blocks but remained constant within each block. The magnitude of the ARE was measured as a difference in the perception of Vernier lines computed between these two circle location conditions.

Crucially, the circles were rather small or rather large in different blocks of trials. The assumption was that the size of the attentional focus for each circle would adapt to the size of that circle and to its location (see also e.g., Goodhew, Shen, & Edwards, 2016). Thus, the ARE should be smaller in blocks with larger circles than in blocks with smaller circles.

2.1. Methods

2.1.1. Participants

The attentional repulsion effect is a robust phenomenon that can reliably be measured using only a few observers (e.g. Suzuki & Cavanagh, 1997). The sample size was thus rather arbitrarily determined to be 16 participants prior to data collection and ensured a power of $1 - \beta = 0.80$ for effect sizes of $d_z = 0.67$ (age: $M = 20$ years, $SD = 2$, two males). All participants had normal or corrected-to-normal vision. They gave their written informed consent for the procedures and received course credit for their participation. The study was conducted in accordance with the ethical guidelines (2016) of the German Psychological Society (DGPs) as well as with the Declaration of Helsinki.

2.1.2. Apparatus

The experiment was performed in a moderately illuminated room. A 19′ monitor was in front of the participants at a distance of approximately 65 cm (Fujitsu Siemens P19-1; 1280 × 1024 pixels; 1 pixel = 0.294 mm; 60 Hz). It was centered at approximate eye level. Participant's head was supported by a chin rest. Headphones were used to present an acoustic signal.

2.1.3. Stimuli

Stimuli were presented on a gray background (13 cd/m^2). Number-sign symbols (###) and fixation crosses (0.18 × 0.18°) were light gray (22 cd/m^2), Vernier lines were black (0.1 cd/m^2), circles were blue and question marks were presented in green. The number signs, the fixation cross as well as the question mark always appeared in the center of the screen. The acoustic signal was a short beep tone (1 kHz, 50 ms). Stimulus presentation was controlled using E-Prime software (Version 2.0; Psychology Software Tools, Pittsburgh, PA).

The Vernier lines (0.3° × 0.05°) were presented at 2.1° of eccentricity above and below the fixation cross. The lower line served as a standard stimulus and was aligned with the horizontal position of the fixation cross. The upper line served as a test stimulus. Its horizontal

[1] Originally, Suzuki and Cavanagh (1997) also proposed that the suppression of activity of neurons surrounding the focus of attention could account for the ARE in addition to the mentioned changes in the size and position of RF.

position varied from trial to trial between −0.7° to 0.7° in respect to the horizontal position of the standard stimulus in ten equidistant steps.

The circles were horizontally aligned with the Vernier lines and their origin was 1.9° to the left or to the right of the middle of the screen (and of the position of standard stimulus). The diameter of one of two circles displayed in one trial was either 0.31 (small focus condition) or 3.6° (large focus condition). The diameter of the other circle slightly deviated from one of these values by either 0.052° (small focus condition) or 0.104° (large focus condition).

2.1.4. Procedure and design

Each trial started with three number signs displayed side by side for ~1,000 ms (see Fig. 1a). Then, a fixation cross was displayed for ~500 ms. With the onset of the fixation cross a beep tone was presented indicating the upcoming target stimulus (not shown in Fig. 1a). The fixation cross was replaced either by the Vernier lines or by two circles displayed for ~100 ms. The probability for each type of stimuli was 0.5 and their succession was random with the constraint that no more than two repetitions were possible. Then, in response to a question mark the participants should indicate whether the upper Vernier line is more left (per left mouse button) or more right (per right mouse button) compared with the lower line in case of the Vernier task. When the circles appeared, the task was to indicate the larger circle by pressing the upper or lower arrow keys of the keyboard for the upper and lower circle respectively. Error feedback was presented when the size judgment was incorrect (German word for "wrong" for 250 ms) or when the tasks were mixed up, i.e. when a mouse button was pressed instead of an arrow key and vice versa ("Error, wrong task, the trial will be repeated" for 2000 ms; these events are not shown in Fig. 1a). In the latter case the trial was immediately repeated. The mouse was controlled by the participants' dominant hand, the keyboard by the non-dominant hand.

There were four blocks of trials, which differed in the location and in the size of the circles. The circles could appear either in the upper-left and lower-right quadrants ("top left & bottom right") or in the upper-right and lower-left quadrants ("top right & bottom left") and could be either small or large. Thus, there were four critical conditions resulting from the factorial combination of the factors circle location and circle size. Each block of trials corresponded to one experimental condition and contained 200 trials, 100 of which included the Vernier task, whereas another 100 trials included the circle discrimination task. That is participants completed 800 trials in total across the entire experiment, and there were 200 trials for each of the four possible combinations of circle location and circle size. In each block, each level of test stimulus was repeated 10 times in a random order in case of the Vernier task. For the circle discrimination task, the lower circle was slightly smaller (25 trials) or slightly larger (25 trials) than the upper circle (that had a size of 0.31° or 3.6° in the small and large focus condition, see also "Stimuli") in one half of the trials. For another half of the trials, the upper circle was smaller (25 trials) or larger (25 trials) than the lower circle. The succession of these variations within a block was random. The succession of blocks was also random.

Participants were asked to look at the fixation cross and not to move their eyes. Before the main experiment started participants performed 20 practice trials which were not included in the analysis.

2.1.5. Data analysis

For each of the critical conditions we computed the proportion of trials in which the test stimulus (i.e. the upper Vernier line) was judged to be left of the standard stimulus (i.e. of the lower Vernier line) as a function of the location of the test stimulus (see Fig.S1 in the Supplementary Materials for individual values). These values were then fitted with a psychometric function by using a local model-free fitting procedure (Zychaluk & Foster, 2009). The position at which the test stimulus was chosen with a frequency of 50% was determined for each experimental condition (point of subjective collinearity, PSC). The attentional repulsion effect was measured as a difference in PSC between the "top right & bottom left" and "top left & bottom right" conditions. All statistical analyses concerning the Vernier task were performed including these difference scores. One participant was excluded from further analyses because of low discrimination performance (see Fig.S1 in the Supplementary Materials).

2.2. Results and discussion

2.2.1. Vernier task

A significant repulsion effect was observed when small circles, $t(14) = 12.20$, $p < .001$, $d_z = 3.15$, $1 - \beta = 1.00$[2], as well as when large circles, $t(14) = 7.40$, $p < .001$, $d_z = 1.91$, $1 - \beta = 1.00$, were used in the size discrimination task (one-sample t-tests against zero). The magnitude of the ARE, however, was smaller for the larger circles as predicted, $t(14) = 2.26$, $p = .040$, $d_z = 0.58$, $1 - \beta = 0.69$ (paired-sample t-test; see Fig. 1c and d).

2.2.2. Size discrimination task

The accuracy in the size discrimination task was on average 0.90 ($SD = 0.06$) for the small circles and 0.74 ($SD = 0.08$) for the large circles. This difference was statistically significant, $t(14) = 7.73$, $p < .001$, $d_z = 2.00$, $1 - \beta = 1.00$ (paired-sample t-test).

We thus observed a smaller ARE with a larger focus of attention as predicted. Because the size discrimination task was somewhat easier in the small compared with the large focus condition, the observed modulation of the ARE could, in theory, be due to a difference in task complexity. To test for this possibility, we correlated the difference in the magnitude of the ARE between both attentional conditions with the difference in the accuracy of the size discrimination task between both attentional conditions across participants. The according correlation coefficient was not significant, $r = 0.07$, $p = .814$, suggesting that the observed modulation of the ARE is not due to changes in task complexity. We also ran an analysis of variance (ANOVA) on ARE scores with focus size as a factor including the difference in the accuracy of the size discrimination mentioned above as a covariate according to a reviewer's suggestion. This analysis did not reveal significant results, $F(1, 13) = 1.36$, $p = .264$, $\eta_p^2 = 0.095$, $F(1, 13) = 0.26$, $p = .619$, $\eta_p^2 = 0.020$, and $F(1, 13) = 0.058$, $p = .814$, $\eta_p^2 = 0.004$, for the main effects of focus size and accuracy difference, and for the interaction respectively, indicating the possibly that the observed ARE change could be due to a change in task complexity yet.

Overall, the results of Exp. 1 confirmed that the used experimental protocol was able to capture a robust ARE and its changes following changes in attentional spread.

3. Experiment 2

Exp. 1 revealed evidence for the impact of the size of the attentional field on the magnitude of the ARE. The goal of Experiment 2 was to replicate and to extend these results. Although the observed modulation of the ARE with focus size was in the predicted direction its magnitude was rather small and some doubts remained whether the focus size rather than task difficulty was its origin. We conjectured that this could be due to a rather marginal manipulation of attentional spread. One clue for this conjecture was evident in Exp.2 of Kosovicheva et al. (2010) that revealed a significant decrease in the ARE when the contours of ovals crossed the vertical meridian (see "large oval cue" condition). In Exp. 2 we thus tested a broader range of stimuli in the size discrimination task in an attempt to more rigorously change the size of attentional focus (see Fig. 2a).

[2] These achieved power values (1 − β) were derived post hoc based on the used sample size, the observed effect size and α = 0.05 using G*Power software (Faul, Erdfelder, Lang, & Buchner, 2007).

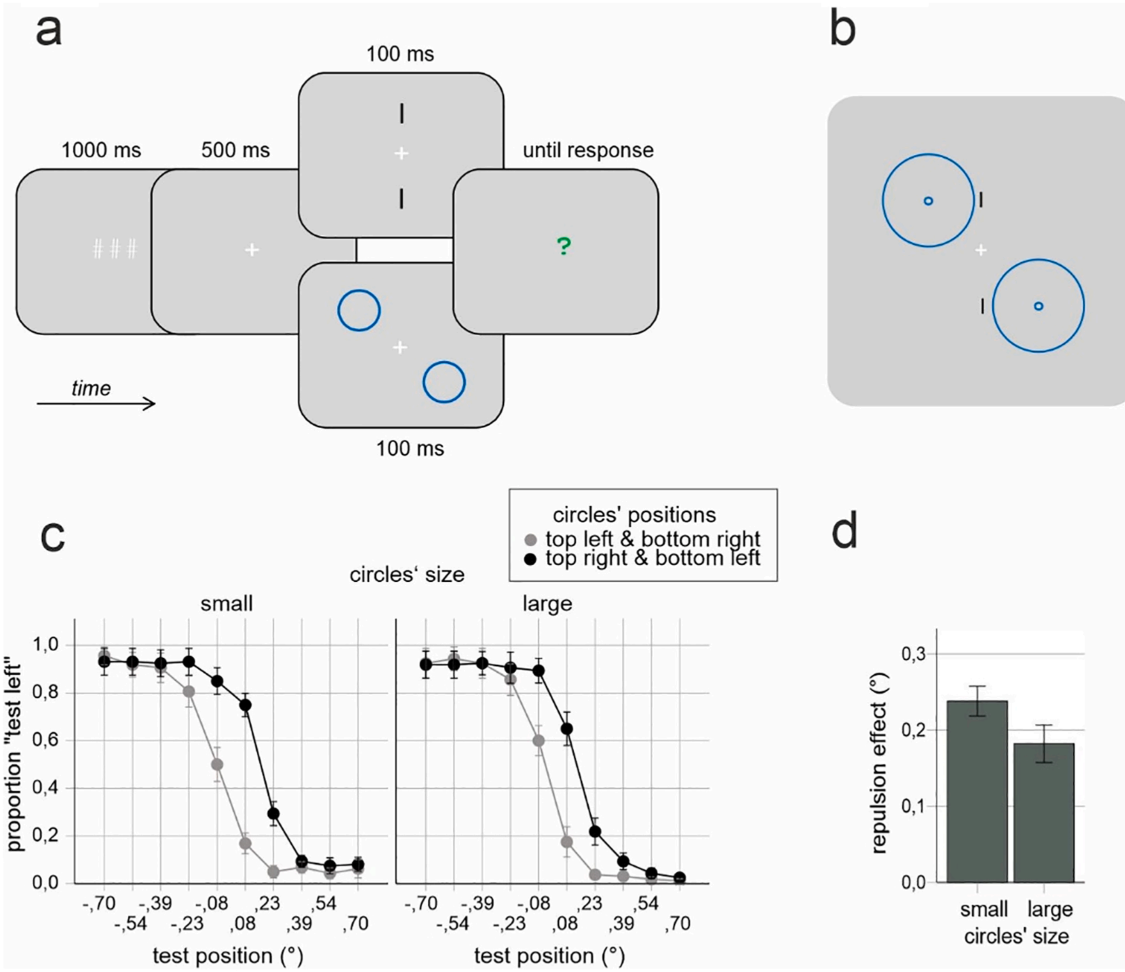

Fig. 1. Experiment 1. (A) Main trial events. (B) Spatial relation between the Vernier lines and the small and large circles. The "top left & bottom right" condition is shown. Stimuli shown in (A) and (B) are not drawn to scale. (C) Mean proportions of "test line left" judgment as a function of the relative size and location of the circles, and of the position of the test line relative to the position of the standard line. Negative/positive values of the test position stand for test line being to the left/right of the standard line. (D) Mean ARE as a function of both circle sizes. Error bars are standard errors indicating the variability across participants.

3.1. Methods

The method of Exp.2 was very similar to the method of Exp.1. We thus describe only the differences below.

3.1.1. Participants

The sample size was a priori determined to be 16 participants. The mean age of the recruited participants was 33 years ($SD = 11$). Three of them were males. None of them participated in Exp.1. The participants received monetary compensation for their participation.

3.1.2. Apparatus

A 21.5′ monitor was in front of the participants at a distance of approximately 55 cm (Acer G226HQL; 1920 × 1080 pixels; 1 pixel = 0.248 mm; 60 Hz).

3.1.3. Stimuli

The luminance of the background was now 16 cd/m^2, of the Vernier lines 3 cd/m^2, and of the fixation cross and of the number-sign symbols 24 cd/m^2. No acoustic stimuli were presented in Exp.2. The horizontal position of the upper line of the Vernier task (test stimulus) varied between −0.54° to 0.54° in respect to the horizontal position of the standard stimulus in eight equidistant steps (the outer test stimuli which appeared redundant were omitted, see Fig. 1c).

In Exp.2 four attentional conditions were implemented. In addition to the small attentional condition ("size 1" hereafter) in which small circles were used as in Exp.1, we used ovals elongated along the horizontal to a varying extent. In particular, the width of one of two ovals presented on one trial was either 6° ("size 2"), 12° ("size 3") or 18° ("size 3"). The height of these stimuli was equal and amounted to 3.6°. The size of the second oval varied from trial to trial between 0.96 and 1.04% in respect to the size of the first oval (i.e. the width and the height of the second oval was about 4% smaller or larger than the width and height of the first oval).

3.1.4. Procedure and design

The trial procedure in Exp. 2 was the same as in Exp.1 except for the acoustic signal that was omitted in Exp.2 (see Fig. 1a). There were eight critical conditions (4 (attentional field size) × 2 (locus of attention)), which were again presented in a block wise manner in a random succession. Each block included 160 trials. A half of these trials included the Vernier task, another half included the size discrimination task. In each block, each level of test stimulus was repeated 10 times in a random order in case of the Vernier task. For the size discrimination task, the lower circle/oval was 4% smaller (20 trials) or 4% larger (20 trials) than the upper circle/oval in one half of the trials. For another half of the trials, the upper circle/oval was smaller (20 trials) or larger (20 trials) than the lower circle/oval. The succession of these size variations within a block was random.

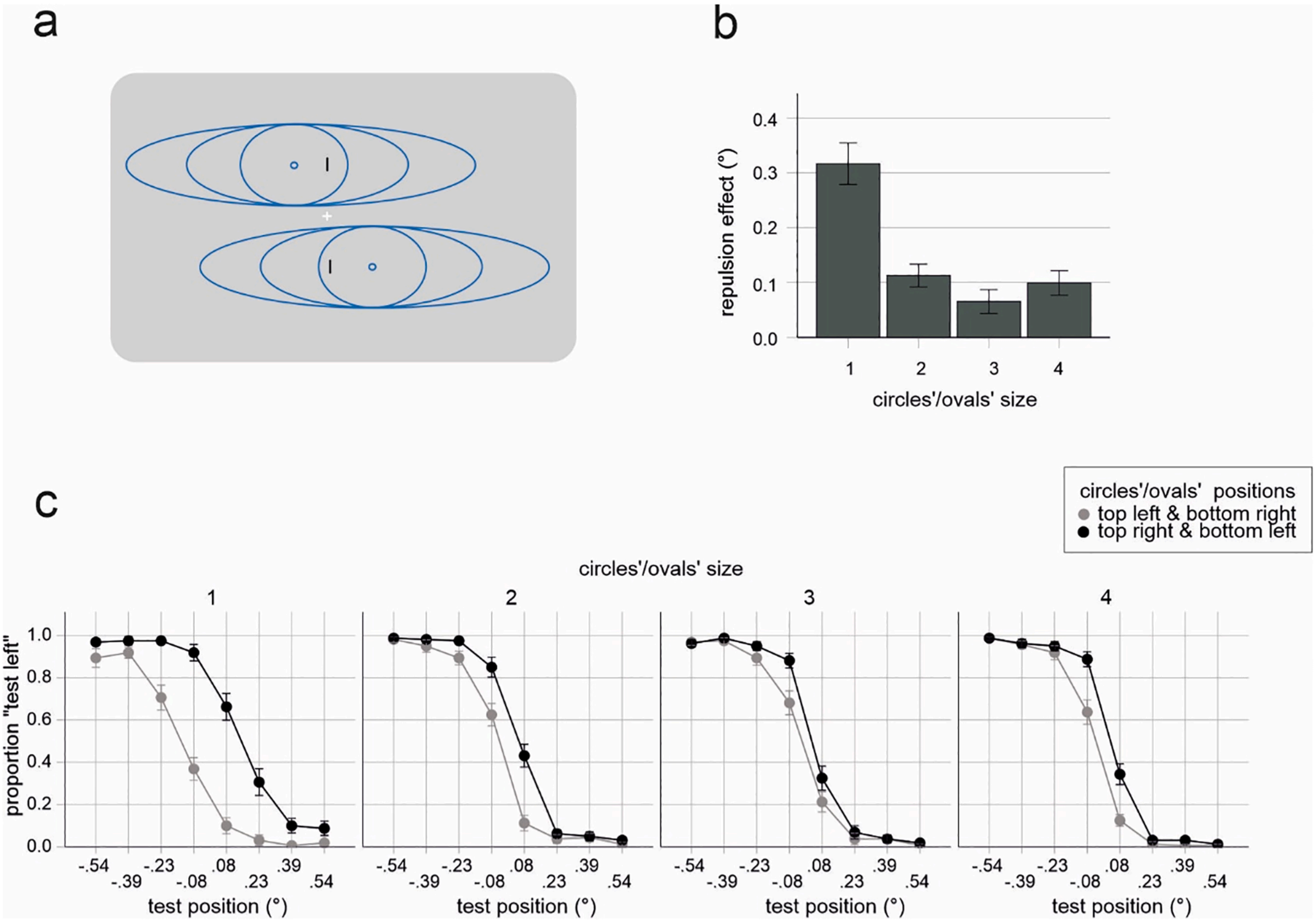

Fig. 2. Experiment 2. (A) Spatial relation between the Vernier lines and the differently sized stimuli used in the size discrimination task. The "top left & bottom right" condition is shown. Stimuli are not drawn to scale. (B) Mean ARE as a function of four circle sizes. (C) Mean proportions of "test line left" judgment as a function of the relative size and location of the circles, and of the position of the test line relative to the position of the standard line. Negative/positive values of the test position stand for test line being to the left/right of the standard line. Error bars are standard errors indicating the variability across participants.

3.1.5. Data analysis

Data analysis was performed in an analogous was as in Exp.1 (see Fig.S2 in the Supplementary Materials for the individual data of the Vernier task).

3.2. Results and discussion

3.2.1. Vernier task

A significant repulsion effect was observed for all attentional field size conditions, $t(15) = 8.39$, $p < .001$, $d_z = 2.10$, $1 - \beta = 1.00$, $t(15) = 5.45$, $p < .001$, $d_z = 1.36$, $1 - \beta = 1.00$, $t(15) = 3.03$, $p = .009$, $d_z = 0.76$, $1 - \beta = 0.90$, and $t(14) = 4.41$, $p = .001$, $d_z = 1.10$, $1 - \beta = 0.99$, for the circle/oval sizes 1, 2, 3, and 4 respectively (one-sample t-tests against zero). The magnitude of the ARE decreased substantially with an increase in focus size, as indicated by a significant main effect of focus size in an analysis of variance (ANOVA) including focus size as a within-subject factor, $F(3, 45) = 30.04$. $p < .001$, $\eta_p^2 = 0.667$, $1 - \beta = 1.00$ (see Fig. 2b for mean values). Bonferroni adjusted pairwise comparisons revealed significant differences between circle/oval size 1 and all other conditions (all $p < .001$; other p-values: 0.580 (2 vs 3), 1.000 (2 vs 4), 1.000 (3 vs 4)).

3.2.2. Size discrimination task

The accuracy in the size discrimination task was on average 0.89 ($SD = 0.12$), 0.87 ($SD = 0.12$), 0.84 ($SD = 0.11$) and 0.82 ($SD = 0.11$) for the circle/oval size conditions 1 to 4 respectively. This decrease in performance with an increase in focus size was significant, $F(3, 45) = 4.58$, $p = .007$, $\eta_p^2 = 0.234$, $1 - \beta = 0.86$ (for a main effect of focus size in a within-subject ANOVA). To ensure that the ARE modulation is not due to task difficulty we correlated the difference in the magnitude of the ARE computed between size 1 and all other size conditions with the difference in the accuracy of the size discrimination computed in an analogous way. The according correlation coefficient was not significant, $r = 0.17$, $p = .535$. We also repeated the main analysis (ANOVA on PSE difference scores with focus size as a factor) including the difference in the accuracy of the size discrimination mentioned above as a covariate. This analysis still revealed a significant main effect of focus size, $F(3, 42) = 17.63$, $p < .001$, $\eta_p^2 = 0.557$, additionally to a non-significant main effect of accuracy difference, $F(1, 14) = 0.70$, $p = .417$, $\eta_p^2 = 0.048$, and a non-significant interaction, $F(3, 42) = 0.62$, $p = .609$. These analyses suggest that the observed modulation of the ARE is not due to changes in task complexity.

Exp. 2 thus replicated the main results of Exp. 1. Moreover, by a stronger manipulation of the size of attentional focus we also observed a stronger modulation of the ARE (about 25% in Exp1. vs over 60% in Exp2). This outcome further strengthened the assumption that the size of the attentional field impacts the perception of object location. However, because there were no significant differences across the three oval conditions it seems that there is an upper limit of the attentional field, above which attention does not influence perception, at least under the present conditions.

4. Experiment 3

Our previous study on the impact of attention on size perception indicated that increasing the size of the attentional focus can not only reduce attentional influence but also even reverse its impact (Kirsch et al., 2018, see also Introduction). We did not observe such an inversion of the ARE effect in Exp. 1 and 2 and supposed that this could be due to differences in the arrangements of the critical stimuli between our previous and the current study, which could entail different attentional distributions. To cope with the Vernier task the participants of the present study have to allocate their attention along the vertical, at least to a certain degree. In contrast, in our previous study, all critical events occurred along the horizontal. Given the known performance differences between horizontal and vertical dimensions observed in perceptual tasks (e.g., Carrasco, Talgar, and Cameron, 2001), we reasoned that the lack of the ARE inversion with focus size could be due to the vertical arrangement of the Vernier lines. Accordingly, we used a horizontal version of the Vernier task in Exp. 3 to explore this possibility (see Fig. 3a).

4.1. Methods

The method of Exp. 3 was identical to the method of Exp. 2 except for the participants sample and the spatial arrangement of the stimuli.

4.1.1. Participants

Sixteen participants participated in Exp.3. The mean age was 26 (*SD* = 5). Five were males. None of them participated in Experiment 2 and all received monetary compensation for their participation.

4.1.2. Stimuli

Vernier line were now presented to the left and to the right of the fixation cross. The left line served as a test stimulus and its vertical position varied from trial to trial between −0.54° to 0.54° in respect to the vertical position of the standard stimulus in eight equidistant steps. The circles and the ovals were now vertically aligned with the Vernier lines and the ovals now elongated along the vertical (see Fig. 3a). Also, the number-sign symbols were now vertically arranged.

4.1.3. Procedure and design

In response to the question mark the participants should indicate whether the left Vernier line is above (upper arrow key of the keyboard) or below (lower arrow key) the right Vernier line in case of the Vernier task. In the circle task, they were to indicate the larger circle by pressing the left or right mouse button for the left or right circle respectively. The mouse was now controlled by the participants' non-dominant hand, the keyboard by the dominant hand.

4.1.4. Data analysis

For each of the critical attentional conditions we computed the proportion of trials in which the test stimulus (i.e. the left Vernier line)

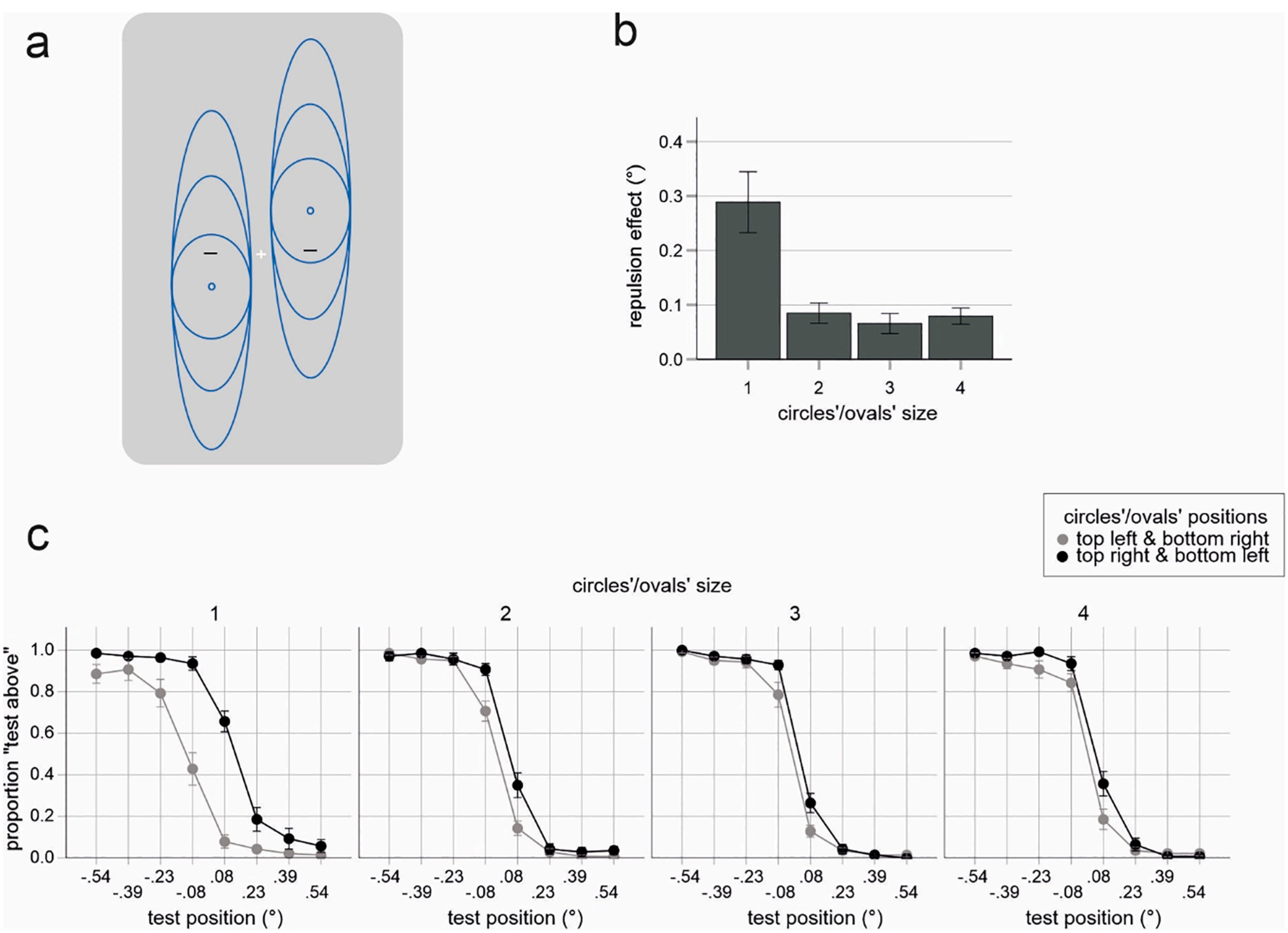

Fig. 3. Experiment 3. (A) Spatial relation between the Vernier lines and the differently sized stimuli used in the size discrimination task. The "top right & bottom left" condition is shown. Stimuli are not drawn to scale. (B) Mean ARE as a function of four circle sizes. (C) Mean proportions of "test line above" judgment as a function of the relative size and location of the circles, and of the position of the test line relative to the position of the standard line. Negative/positive values of the test position stand for test line being above/below of the standard line. Error bars are standard errors indicating the variability across participants.

was judged to be above the standard stimulus (i.e. the right Vernier line) as a function of the location of the test stimulus. The attentional repulsion effect was measured as a difference in PSC between the "top right & bottom left" and "top left & bottom right" conditions. Two participants were excluded from analyses because of low discrimination performance (see Fig.S3 in the Supplementary Materials).

4.2. Results and discussion

4.2.1. Vernier task

A significant repulsion effect was observed for all attentional field size conditions, $t(13) = 5.17$, $p < .001$, $d_z = 1.38$, $1 - \beta = 1.00$, $t(13) = 4.58$, $p = .001$, $d_z = 1.22$, $1 - \beta = 1.00$, $t(13) = 3.61$, $p = .003$, $d_z = 0.96$, $1 - \beta = 0.96$, and $t(13) = 5.30$, $p < .001$, $d_z = 1.42$, $1 - \beta = 1.00$, for the circle/oval sizes 1, 2, 3, and 4 respectively (one-sample t-tests against zero). The ARE decreased with an increase in focus size, $F(3, 39) = 13.17$, $p < .001$, $\eta_p^2 = 0.503$, $1 - \beta = 1.00$ (main effect of focus size in an ANOVA including focus size as a within-subject factor; see Fig. 3b and c). Bonferroni adjusted pairwise comparisons revealed significant differences between size 1 and all other conditions (all $p \leq 0.19$; other p-values: 1.000 (2 vs 3), 1.000 (2 vs 4), 1.000 (3 vs 4)). These results were not significantly different from the results of Exp.2, as indicated by the results of an ANOVA including experiment as a between-subject factor and focus size as a within-subject factor. This analysis revealed a non-significant interaction between both factors, $F(3, 84) = 0.14$, $p = .933$, $\eta_p^2 = 0.005$.

4.2.2. Size discrimination task

The accuracy in the size discrimination task was on average 0.91 ($SD = 0.09$), 0.83 ($SD = 0.12$), 0.84 ($SD = 0.10$) and 0.84 ($SD = 0.13$) for the circle/oval size conditions 1 to 4 respectively. This decrease in performance with an increase in focus size was significant, $F(3, 39) = 5.45$, $p = .003$, $\eta_p^2 = 0.296$, $1 - \beta = 0.91$ (for a main effect of focus size in a within-subject ANOVA). The difference in the magnitude of the ARE between attentional conditions (size 1 minus all other) and the analogous difference in the accuracy of the size discrimination size did not correlate, $r = 0.058$, $p = .844$. The main analysis (ANOVA on PSE difference scores with focus size as a factor) including the difference in the accuracy of the size discrimination mentioned above as a covariate still revealed a significant main effect of focus size, $F(3, 36) = 5.30$, $p = .004$, $\eta_p^2 = 0.306$, additionally to a non-significant main effect of accuracy difference, $F(1, 12) = 0.04$, $p = .841$, $\eta_p^2 = 0.003$, and a non-significant interaction, $F(3, 36) = 0.16$, $p = .925$. These analyses suggest that the observed modulation of the ARE is not due to changes in task complexity.

The results of Exp.3 were very similar to the results of Exp.2. We thus again replicated a decrease in ARE with an increase in focus size. An inversion of the effect suspected for the horizontal arrangement of the Vernier stimulus was, however, not observed. We return to this point in the next section.

5. General discussion

The present study examined the influence of the size of attended spatial area on the repulsion of perceived object location from the focus of attention, i.e. on the ARE. The results of three experiments were reasonably consistent. The ARE substantially decreased with an increase in attentional spread. This outcome is consistent with the predictions of current models of attentional influences on perception linking neurophysiology and behavior and indicates changes in RF characteristics following changes in the size of attentional field (Baruch & Yeshurun, 2014; Klein et al., 2016). In particular, a decrease in the magnitude of the shift of RF towards the center of attention can account for the decrease of the ARE with larger attentional distribution.

A similar mechanism can also potentially explain previous related observations, such as a modulation of foveal bias with changes in attentional distribution. In a typical experiment, the participant fixates a central location while a target stimulus is flashed in the periphery. The location of the target stimulus is misperceived as being closer to the point of fixation than it actually is. This foveal bias is larger under conditions of distributed than of focused attention (Bocianski et al., 2010; Fortenbaugh & Robertson, 2011). Now consider that RF of cortical neurons should drift towards the center of attention. Accordingly, adopting a broad focus of attention centered at the fixation could entail a smaller drift of RF towards the fovea than conditions of focused attention in which attention can be assumed to be more focused at the point of fixation.[3] As a smaller RF drift towards the fovea means less repulsion from the fovea, the foveal bias is larger with distributed attention. Also of note, the foveal bias usually increase with distance of the target from the fixation. This could also be due to a decrease of RF shifts (and thus a decrease of perceptual repulsion) with distance from the focus of attention. These assumptions are of course tentative at present and require further research.

The present results are also consistent with our previous study on size perception in that apparent size decreased with an increase in focus size (Kirsch et al., 2018). However, in that study an increase in attentional spread completely reversed the effect of attention observed with a small attentional focus. Such an inversion of the ARE was not observed in the present study. There are at least two possible explanations for this outcome. First, in spite of an overlap, the impact of attention on size perception does not rely on the exactly same mechanism as the impact of attention on location perception. Second, some procedural differences between the studies are responsible for partly different results. For example, in the previous study a single exogenous cue and an equivalent endogenous variation were used. In the present study, in contrast, a "double-cue procedure" was applied, in which both critical stimuli (i.e. Vernier lines) were subject to attentional manipulation. Thus, the attentional distributions induced in two studies could be not directly comparable with each other.

In the present study, participants discriminated between unfilled circles and ovals and we assumed that attention is distributed across the whole area of these shapes. However, it has been recently suggested that observers may rather adopt an annulus shaped distribution of attention under such conditions (Lawrence, Edwards, & Goodhew, 2020). This would imply that participants focus their attention mainly on the contours of a shape. Such a scenario cannot be easily reconciled with the present and previous related results observed with the ARE paradigm. As the data of Kosovicheva et al. (2010) suggest, attention is shifted to the center of a shape used as exogenous cue, rather to its contours. In the present study, the location of contours relative to the Vernier line does also not appear to play a substantial role though we cannot exclude this possibility as we did not systematically address this issue. Consider that the effect is of the same direction whether the contour is left or right of the Vernier line (see Exp.1 and Exp.2). Also, oval conditions 2, 3, and 4 did not differ from each other although they substantially differ in contours. These are of course only indirect indices and more research is needed to examine this issue in more detail.

To sum up, the present results add to the increasing evidence for the impact of attention on visual appearance and suggest that the size of attentional focus modulates the perception of object location. Whether and how attentional spread affects the characteristics of object' appearance beyond location and size could be a worthwhile question for future research.

6. Author statement

All authors contributed to the study concept and study design. Data were collected and analyzed by W. Kirsch. All authors collaborated on

[3] Note that in the conditions of focused attention participants attended to a certain area at which the target appeared. Possible RF shifts towards this area are ignored in this rationale.

writing the manuscript and approved its final version for submission.

Acknowledgement

This research was supported by grants KI 1620/3-1 and KI 1620/3-2 awarded to W. Kirsch by the German Research Council (DFG). The data are publicly available via the Open Science Framework at https://osf.io/28hbg/.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.visres.2020.11.004.

References

Anton-Erxleben, K., & Carrasco, M. (2013). Attentional enhancement of spatial resolution: Linking behavioral and neurophysiological evidence. *Nature Reviews Neuroscience, 14*, 188–200.

Anton-Erxleben, K., Henrich, C., & Treue, S. (2007). Attention changes perceived size of moving visual patterns. *Journal of Vision, 7*(11), 5. https://doi.org/10.1167/7.11.5.

Anton-Erxleben, K., Stephan, V. S., & Treue, S. (2009). Attention reshapes center-surround receptive field structure in macaque cortical area MT. *Cerebral Cortex, 19*, 2466–2478.

Arnott, S. R., & Goodale, M. A. (2006). Distorting visual space with sound. *Vision Research, 46*(10), 1553–1558. https://doi.org/10.1016/j.visres.2005.11.020.

Baruch, O., & Yeshurun, Y. (2014). Attentional attraction of receptive fields can explain spatial and temporal effects of attention. *Visual Cognition, 22*(5), 704–736. https://doi.org/10.1080/13506285.2014.911235.

Baumeler, D., Nako, R., Born, S., & Eimer, M. (2020). Attentional repulsion effects produced by feature-guided shifts of attention. *Journal of Vision, 20*(3), 10. https://doi.org/10.1167/jov.20.3.10.

Bocianski, D., Müsseler, J., & Erlhagen, W. (2010). Effects of attention on a relative mislocalization with successively presented stimuli. *Vision Research, 50*(18), 1793–1802. https://doi.org/10.1016/j.visres.2010.05.036.

Carrasco, M., Talgar, C. P., & Cameron, E. L. (2001). Characterizing visual performance fields: Effects of transient covert attention, spatial frequency, eccentricity, task and set size. *Spatial Vision, 15*(1), 61–75. https://doi.org/10.1163/15685680152692015.

Carrasco, M., & Barbot, A. (2019). Spatial attention alters visual appearance. *Current Opinion in Psychology, 29*, 56–64. https://doi.org/10.1016/j.copsyc.2018.10.010.

Carrasco, M., Ling, S., & Read, S. (2004). Attention alters appearance. *Nature Neuroscience, 7*(3), 308–313. https://doi.org/10.1038/nn1194.

Castiello, U., & Umiltà, C. (1990). Size of the attentional focus and efficiency of processing. *Acta Psychologica, 73*(3), 195–209. https://doi.org/10.1016/0001-6918(90)90022-8.

Cutrone, E. K., Heeger, D. J., & Carrasco, M. (2018). On spatial attention and its field size on the repulsion effect. *Journal of Vision, 18*(6), 8. https://doi.org/10.1167/18.6.8.

DiGiacomo, A., & Pratt, J. (2012). Misperceiving space following shifts of attention: Determining the locus of the attentional repulsion effect. *Vision Research, 64*, 35–41. https://doi.org/10.1016/j.visres.2012.05.009.

Eriksen, C. W., & St. James, J. D. (1986). Visual attention within and around the field of focal attention: A zoom lens model. *Perception & Psychophysics, 40*(4), 225–240. https://doi.org/10.3758/BF03211502.

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39*(2), 175–191. https://doi.org/10.3758/BF03193146.

Fortenbaugh, F. C., Prinzmetal, W., & Robertson, L. C. (2011). Rapid changes in visual-spatial attention distort object shape. *Psychonomic Bulletin & Review, 18*(2), 287–294. https://doi.org/10.3758/s13423-011-0061-5.

Fortenbaugh, F. C., & Robertson, L. C. (2011). When becomes there: Attentional distribution modulates foveal bias in peripheral localization. *Attention, Perception & Psychophysics, 73*, 809–828.

Fortenbaugh, F. C., Robertson, L. C., & Esterman, M. (2017). Changes in the distribution of sustained attention alter the perceived structure of visual space. *Vision Research, 131*, 26–36. https://doi.org/10.1016/j.visres.2016.12.002.

Gobell, J., & Carrasco, M. (2005). Attention alters the appearance of spatial frequency and gap size. *Psychological Science, 16*(8), 644–651. https://doi.org/10.1111/j.1467-9280.2005.01588.x.

Goodhew, S. C., Shen, E., & Edwards, M. (2016). Selective spatial enhancement: Attentional spotlight size impacts spatial but not temporal perception. *Psychonomic Bulletin & Review, 23*(4), 1144–1149. https://doi.org/10.3758/s13423-015-0904-6.

Kirsch, W., Heitling, B., & Kunde, W. (2018). Changes in the size of attentional focus modulate the apparent object's size. *Vision Research, 153*, 82–90. https://doi.org/10.1016/j.visres.2018.10.004.

Klein, B., Harvey, B., & Dumoulin, S. (2014). Attraction of position preference by spatial attention throughout human visual cortex. *Neuron, 84*(1), 227–237. https://doi.org/10.1016/j.neuron.2014.08.047.

Klein, B. P., Paffen, C. L. E., Pas, S. F.t., & Dumoulin, S. O. (2016). Predicting bias in perceived position using attention field models. *Journal of Vision, 16*(7), 15. https://doi.org/10.1167/16.7.15.

Kosovicheva, A. A., Fortenbaugh, F. C., & Robertson, L. C. (2010). Where does attention go when it moves?: Spatial properties and locus of the attentional repulsion effect. *Journal of Vision, 10*(12), 33. https://doi.org/10.1167/10.12.33.

Lawrence, R. K., Edwards, M., & Goodhew, S. C. (2020). The impact of scaling rather than shaping attention: Changes in the scale of attention using global motion inducers influence both spatial and temporal acuity. *Journal of Experimental Psychology: Human Perception and Performance, 46*(3), 313–323.

Müller, N. G., Bartelt, O. A., Donner, T. H., Villringer, A., & Brandt, S. A. (2003). A physiological correlate of the "Zoom Lens" of visual attention. *The Journal of Neuroscience, 23*(9), 3561–3565. https://doi.org/10.1523/JNEUROSCI.23-09-03561.2003.

Pratt, J., & Arnott, S. R. (2008). Modulating the attentional repulsion effect. *Acta Psychologica, 127*(1), 137–145. https://doi.org/10.1016/j.actpsy.2007.03.003.

Pratt, J., & Turk-Browne, N. B. (2003). The attentional repulsion effect in perception and action. *Experimental Brain Research, 152*(3), 376–382. https://doi.org/10.1007/s00221-003-1557-7.

Suzuki, S., & Cavanagh, P. (1997). Focused attention distorts visual space: An attentional repulsion effect. *Journal of Experimental Psychology: Human Perception and Performance, 23*, 443–463.

Womelsdorf, T., Anton-Erxleben, K., & Treue, S. (2008). Receptive Field Shift and Shrinkage in Macaque Middle Temporal Area through Attentional Gain Modulation. *Journal of Neuroscience, 28*(36), 8934–8944. https://doi.org/10.1523/JNEUROSCI.4030-07.2008.

Zychaluk, K., & Foster, D. H. (2009). Model-free estimation of the psychometric function. *Attention, Perception, & Psychophysics, 71*, 1414–1425.