Vision Research 153 (2018) 82–90

Contents lists available at ScienceDirect

Vision Research

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

Changes in the size of attentional focus modulate the apparent object's size

Wladimir Kirsch*, Bastian Heitling, Wilfried Kunde

Department of Psychology, University of Würzburg, Germany

ARTICLE INFO

No. of reviewers: 2

Keywords:
Attention
Size perception

ABSTRACT

Previous research has shown that the allocation of spatial attention at a small region of space increases the apparent size of the adjacent spatial area. In four experiments reported here, we systematically induced either small or large foci of attention and examined how this affects the perceived object's size. We observed that an increase in the size of the attentional focus consistently decreased the apparent object's size. This outcome provides new insights into how attention alters appearance.

1. Introduction

A number of studies have revealed that the way objects appear to observers depends on the observers' attention to such objects (e.g., Anton-Erxleben, Heinrich, & Treue, 2007; Carrasco, Ling, & Read, 2004; Fortenbaugh, Prinzmetal, & Robertson, 2011; Fuller & Carrasco, 2006; Gobell & Carrasco (2005); Hock, Balz, & Smollon, 1998; Shulman, 1992). One example is the attentional repulsion effect (ARE): two Vernier lines appear to be displaced away from the current focus of attention (Suzuki & Cavanagh, 1997).

In these studies, the experimental manipulation of attention was often related to a small region of space. Usually, small dots or bars were used as transient cues to direct participants' attention to a certain place (but see Kosovicheva, Fortenbaugh, & Robertson, 2010 for an exception). The assumption is that visual attention is focused on the cued location as compared to uncued locations. Further it has been assumed that by means of a common neurophysiological mechanism attention jointly increases spatial resolution (e.g., Golla, Ignashchenkova, Haarmeier, & Thier, 2004; see also Carrasco & Barbot, 2015 for a review) and changes the appearance of objects at the attended location, as compared to unattended regions of space (Anton-Erxleben & Carrasco, 2013; Baruch & Yeshurun, 2014).

While the links between focus of attention, spatial resolution and object appearance seem generally well supported, more specific predictions can be made. Not only should attending the center of a circular visual stimulus increase its perceived size (Anton-Erxleben et al., 2007). Rather a more systemic relationship should exist: Narrowing the focus of attention should increase perceived object size, and widening the focus of attention should decrease perceived object size (cf. e.g., Baruch & Yeshurun, 2014). This prediction is tested in the present experiments.

The main experimental manipulation in Experiments 1–3 was related to the size of a transient cue preceding a target object. The cue was either substantially smaller or substantially larger than the target. According to previous research we assumed that the spatial extent of the attentional focus will vary with the size of the cue (i.e., it will increase with an increase in cue size; e.g., Castiello & Umilta, 1990; Eriksen and St. James, 1986; Greenwood & Parasuraman, 2004; Yeshurun & Carrasco, 2008). The critical question of interest was how an expansion in the attentional focus would affect the perceived size of the target object. With Experiment 4 we then tested whether the results observed using exogenous attentional cues generalize to situations with rather sustained or endogenous attentional changes.

2. Experiment 1

In Experiment 1, we used a version of the procedure which already proved to be suitable to demonstrate that attention alters the perceived objects' size (Anton-Erxleben et al., 2007; cf. also Carrasco et al., 2004). Participants fixated a central cross before an attentional cue was flashed either peripherally or at the fixated location. Then a pair of circular targets briefly appeared peripherally to the fixation cross and the participants were asked to indicate which target is larger (see Fig. 1).

The size of the cue was varied: the cue could be either smaller or larger than the target. According to previous research the small cue was expected to increase the apparent size of the target at the cued side of the display as compared with a neutral condition where the cue was presented at the fixated location (Anton-Erxleben et al., 2007). The critical question here was whether the large cue will produce a decrease in perceived target size.

2.1. Methods

2.1.1. Ethics statement

The present research was conducted in accordance with the Declaration of Helsinki.

* 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.2018.10.004
Received 28 March 2018; Received in revised form 8 October 2018; Accepted 11 October 2018
0042-6989/

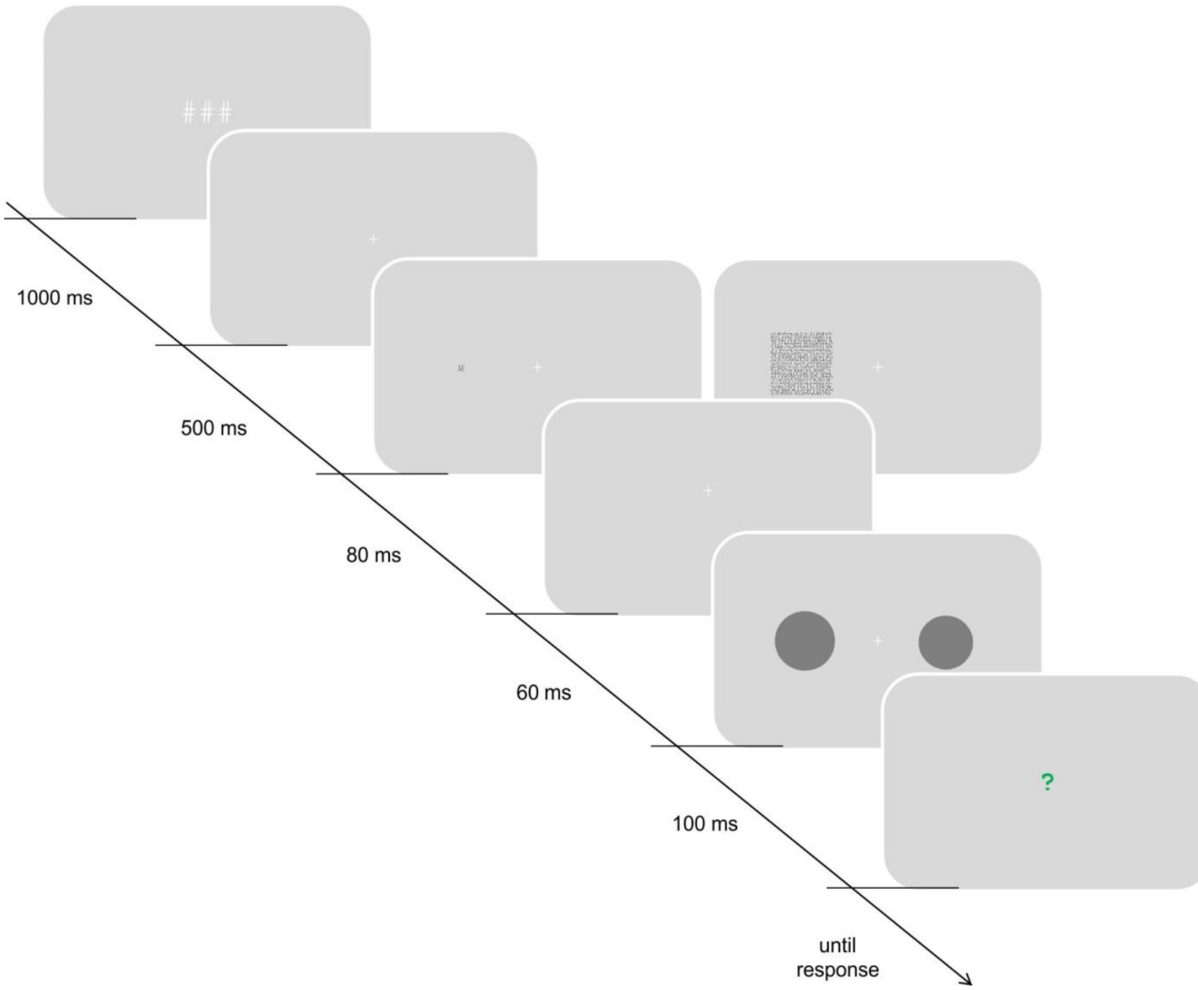

Fig. 1. The temporal structure of a single trial in Experiment 1.

2.1.2. Participants

Twelve right-handed participants participated in Experiment 1. All were naive to the purpose of the experiment and had normal or corrected-to-normal vision. The sample included eleven females and one male (M_{age} = 25, SD = 3). Participants gave their informed consent for the procedures and received monetary compensation for their participation.

2.1.3. Apparatus

Experiment was performed in a dim experimental room. Stimuli were displayed on a CRT monitor (19″, Samsung Samtron 96 B, Samsung), with a resolution of 1024 × 768 pixels and a 100-Hz refresh rate. One pixel (px) measured about 0.35 mm on the screen. Observers were seated at a 65-cm distance from the screen with their head supported by a combined chin-and-forehead rest.

2.1.4. Stimuli

All stimuli were presented on a gray background (with coordinates "128, 128, 128" in the RGB color space). The number sign symbols (###) shown during the intertrial interval as well as the fixation cross were light gray (175, 175, 175), whereas cues and targets were presented in dark gray (with RGB-coordinates "36, 36, 36" and "81, 81, 81" respectively). The question mark was green. The number signs, fixation cross and the question mark always appeared in the middle of the screen. The circular targets were presented at 4° eccentricity left and right of the fixation cross. The same positions could also be occupied by the cue. Additionally, however, the cue could also appear at the position of the fixation cross (see below). The cues were unframed squares which were filled with dots about 0.03° in size. The dots had random distances between 0.06° and 0.12° along the horizontal and fixed distances of 0.09° along the vertical (see Fig. 1 for examples). The arrangement of dots randomly varied across the six cue conditions (see below) and across the participants. For each participant and each cue condition, however, it was constant throughout the experiment[1]. Stimulus presentation and recording of participants' responses were controlled using the E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA).

2.1.5. Procedure and task

The main trial events are shown in Fig. 1. At the beginning of each trial three number sign symbols appeared for 1000 ms (intertrial interval). Then, a fixation cross was displayed. Following 500 ms a cue was flashed (for 80 ms). Following another 60 ms two circular targets were presented laterally to the fixation cross for 100 ms. Finally, in response to a question mark the participants should indicate which of the circles appeared larger by pressing the left or the right key of a computer mouse. The cues should be ignored.

2.1.6. Design

One of the two presented circles was always the standard stimulus with a constant size (2° in diameter) that could appear either left or

[1] There were mainly practical reasons for not to randomize the arrangement for each trial (such as temporal delays in E-Prime).

right. The size of the other circle (test stimulus) varied from 87.5% to 112.5% of the standard diameter in nine steps. The cue could be rather small (0.5° side length) or rather large (3.9°) and could appear either at the position of the left circle or the right circle or at the position of the fixation cross as mentioned. There were thus 54 experimental conditions (test size (9) x cue size (2) x cuing condition (3)) which were randomly presented. The main experiment was divided in five blocks of trials with 216 trials each and included 20 repetitions of each condition. Before the main experiment started participants performed 72 practice trials which were not included in the analysis.

2.1.7. Data analysis

For each participant and each cue size, we computed the proportion of trials in which standard stimulus was cued, test stimulus was cued, the cue was at the position of the fixation cross (neutral cue), and the test stimulus was judged as larger as a function of the test size. These values were then fitted with a psychometric function using a local model-free fitting procedure (mean $r^2 = 0.95$, $SD = 0.05$) and the point of subjective equality (PSE) was determined (Zychaluk & Foster, 2009). The PSE reflects the size of the test stimulus at which both the standard and the test stimulus appear equal and is calculated by identifying the test size at which the psychometric function crosses the 50% threshold. The PSE values were statistically analyzed using SPSS software (Version 23, Armonk, NY: IBM Corp.).

2.2. Results

One participant was excluded from analyses due to a very low discrimination performance (see Fig. S1). Mean proportions of trials in which the test stimulus was judged as larger are shown in Fig. 2 (left and middle parts). In the neutral cue conditions the PSE was about 1, i.e., the perceived size of the stimulus corresponded quite exactly to its physical size for both sizes of the cue. When the cue was small and the test stimulus was cued, the PSE shifted to the left by about 6%. When the cue was small and the standard stimulus was cued, the PSE shifted to the right by about 7%. As shown in Fig. 2, the results are reversed for the large attentional cue: the PSE shifted to the right (9%) when the test stimulus was cued and to the left (7%) when the standard stimulus was cued. This pattern was observed for each participant (cf. Fig. S1).

An analysis of variance (ANOVA) including cuing condition (test cued, neutral cue, standard cued) and cue size (small, large) as within-subjects factors and PSE values as a dependent measure revealed a significant main effect of cue size, $F(1, 10) = 5.52$, $p = .041$, $\eta_p^2 = 0.356$, and importantly, a significant interaction between both factors, $F(2, 20) = 127.83$, $p < .001$, $\eta_p^2 = 0.927$. Follow-up analyses (t-tests) showed that the means of all levels of the factor cueing condition differed significantly from each other for each cue size (all $p < .001$).

2.3. Discussion

The main finding of Experiment 1 was clear-cut. The size of the cue strongly affected the judgments of objects' size. When attention was directed to a small central region of an object by a small exogenous cue that object was judged as larger (than when the object was unattended). This outcome is a conceptual replication of results from a previous study (Anton-Erxleben et al., 2007). The novel observation here is that the supposed expansion of attention by a large cue led to an opposite pattern of results. That is, the object was judged as smaller as compared with a neutral attention condition.

One could raise some concerns whether the effects we observed are perceptual in nature. In other words, do the observed changes in judgment behavior really reflect changes in size perception? Experiment 2 examined this question.

3. Experiment 2

A possible problem of Experiment 1 could be that, if subjects must decide which of two objects is larger, and if one of the objects is cued, then that object may be chosen by the subjects for reasons that have nothing to do with the size (cf. e.g., Kerzel, Zarian, Gauch, & Buetti, 2010; Prinzmetal, Long, & Leonhardt, 2008; Schneider & Komlos, 2008). In particular, both attentional cues could be used as a reference to a varying degree when making the comparison judgment.

To distinguish such a response bias from a perceptual explanation we varied the type of participants' decisions in Experiment 2. In contrast to Experiment 1 where comparative judgments were required ("which object is larger") we now used an equality judgment. That is the participants were asked to choose whether the two objects are equal in size or not. The effects of the decision criterion in this equality judgment are distinguishable from the effects of actual changes in appearance (cf e.g., Schneider, 2011; Schneider & Komlos, 2008; but see Anton-Erxleben, Abrams, & Carrasco, 2011). If the effects observed in Experiment 1 vanish in Experiment 2 then the observed impact of the attentional cues on size judgments should be attributed to decision bias. Otherwise the observed effects should reflect changes in size perception.

3.1. Methods

3.1.1. Participants

Twelve right-handed participants participated in Experiment 2.

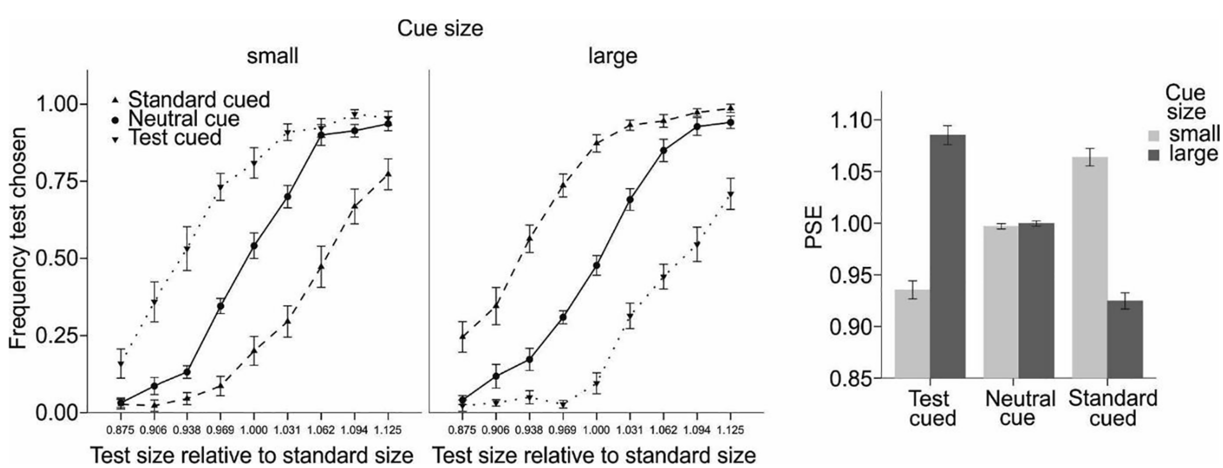

Fig. 2. Main results of Experiment 1. The percentage of trials for test cued, neutral and standard cued trials in which the test stimulus was judged as larger for the small (left part) and large (middle part) cue. The according PSE values are on the right side of the figure. Error bars are standard errors.

None of them participated in Experiment 1. All were naive to the purpose of the experiment and had normal or corrected-to-normal vision. The sample included ten females and two males (M_{age} = 26, *SD* = 7). Participants gave their informed consent for the procedures and received either monetary compensation or course credit for their participation.

3.1.2. Procedure and task

After a question mark appeared the participants were required to indicate whether the circles were the same or different in size. For one half of them the left mouse button was assigned to the response “same” and the right mouse button to the response “different”. For the other half of the participants this assignment was reversed. The rest of the procedure was as in Experiment 1.

The *Design, Apparatus and Stimuli* were the same as in Experiment 1.

3.1.3. Data analysis

We computed the proportion of trials in which the standard stimulus was cued, the test stimulus was cued, the cue was at the position of the fixation cross (neutral cue), and the test stimulus was judged as being of the same size as the standard stimulus as a function of the test size. The data of some participants did not exhibit clearly detectible local maxima within the used range of test stimuli (cf. Fig. S2). For this reason we analyzed the judgment data directly using ANOVAs.

3.2. Results

Mean proportions of trials in which the test stimulus was judged as being of the same size as the standard stimulus are shown in Fig. 3. In the neutral cue conditions the maximum of the same responses was achieved when the size of the test stimulus corresponded to the size of the standard stimulus for both sizes of the cue. When the cue was small and the test stimulus was cued, the psychometric function shifted to the left by about 6%. When the cue was small and the standard stimulus was cued, a rightward shift of about 6% was evident. As shown in Fig. 3, the results are reversed for the large attentional cue: the function shifts to the right when the test stimulus was cued and to the left when the standard stimulus was cued. This pattern is clearly observable in the individual data (cf. Fig. S2).

An ANOVA was performed including cuing condition (test cued, neutral cue, standard cued), cue size (small, large) and test size (from 87.5% to 112.5% of the standard size) as within-subjects factors and frequency of same decisions as a dependent measure. The critical three-way interaction was significant, $F(16,\ 176) = 36.79$, $p < .001$, $\eta_p^2 = 0.770$. Follow-up analyses (ANOVAs) showed that the factors test size and cuing condition significantly interact with each other when the small and the large cue conditions were separately analyzed, $F(16,\ 176) = 19.94$, $p < .001$, $\eta_p^2 = 0.644$, and $F(16,\ 176) = 25.84$, $p < .001$, $\eta_p^2 = 0.701$.

3.3. Discussion

The results of Experiment 2 were unequivocal. The impact of the attentional cues on size judgments observed in Experiment 1 using comparative judgments was clearly evident in Experiment 2 using equality judgments that are resistant to response bias. Accordingly, the size of an exogenous attentional cue seems in fact to critically affect how large objects appear. This, however, does not necessarily imply that changes in attention are responsible for the observed changes in size perception. This issue was explored in Experiments 3 and 4.

4. Experiment 3

The results of the previous experiments could be due to some low-level interactions between the cue and the target rather than due to changes in attentional focus as we assumed. For example, the cue could mask the target to some extent and this could affect the apparent target size. This concern is especially related to the large cue condition as the cue completely encompasses the target stimulus. To test for this possible confound we replaced the filled-in quadratic cues used Experiments 1 and 2 by more common unfilled cues (squares) in Experiment 3 (cf. e.g., Castiello & Umilta, 1990; Greenwood & Parasuraman, 2004; Yeshurun & Carrasco, 2008). As a result, the critical large cue now surrounded the target and thus masked it to a much lesser degree if at all. If the effects observed in Experiments 1 and 2 are due to sensory forward masking of the target by the cue, they should disappear in Experiment 3. This should especially be true for the large cue condition. Otherwise, low-level cue target interactions can be assumed to not essentially contribute to the observed effects.

4.1. Methods

4.1.1. Participants

Twelve right-handed participants participated in Experiment 3. None of them participated in Experiment 1 and one of them

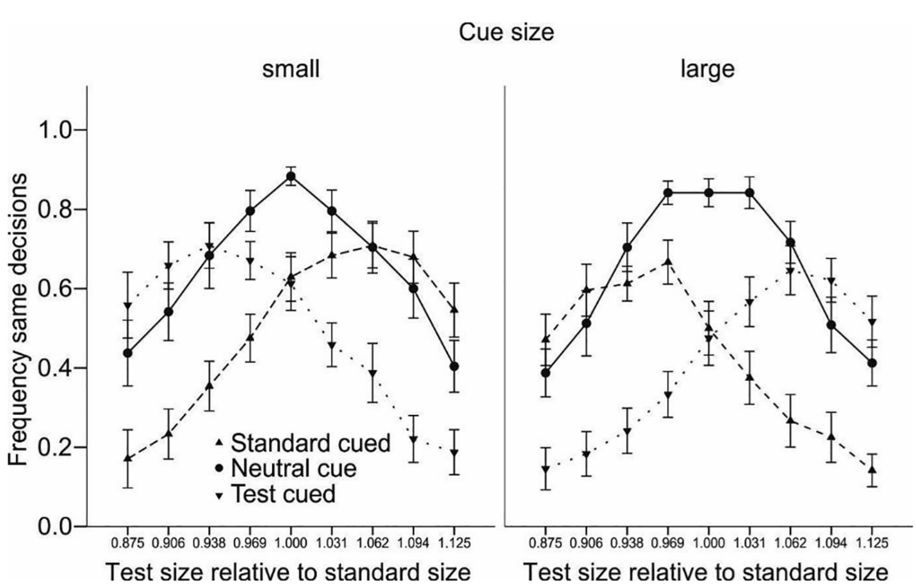

Fig. 3. Main results of Experiment 2. The percentage of trials for test cued, neutral and standard cued trials in which the test stimulus was judged as being of the same size as the standard stimulus for the small and large cue. Error bars are standard errors.

participated in Experiment 2. All were naive to the purpose of the experiment, had normal or corrected-to-normal vision, and were paid for their participation. The sample included six females and six males (M_{age} = 27, SD = 6).

4.1.2. Stimuli

The stimuli were the same as in Experiment 1 with the following change. Dark gray ("36, 36, 36") unfilled squares of 0.5° or 3.9° side length now served as cues. The thickness of the outline was 0.03°.

The *apparatus*, *procedure*, *task*, *design* and *data analyses* were the same as in Experiment 1. The data fitting procedure revealed a mean r^2 of 0.96 (SD = 0.03).

4.2. Results

Two participants were excluded from analyses due to a very low discrimination performance (see Fig. S3). Mean proportions of trials in which the test stimulus was judged as larger are shown in Fig. 4 (left and middle parts). The observed pattern of results was as in Experiment 1. In the neutral cue conditions the perceived size of the stimulus corresponded well to its physical size. When the cue was small and the test stimulus was cued, the PSE shifted to the left (by about 5%). When the cue was small and the standard stimulus was cued, the PSE shifted to the right (6%). The results are reversed for the large attentional cue: the PSE shifted to the right (7%) when the test stimulus was cued and to the left (6%) when the standard stimulus was cued (cf. Fig. S3 for individual data).

An analysis of variance (ANOVA) including cuing condition (test cued, neutral cue, standard cued) and cue size (small, large) as within-subjects factors and PSE values as a dependent measure revealed a significant interaction between cue size and cuing condition, $F(2, 18) = 54.42$, $p < .001$, $\eta_p^2 = 0.858$. Follow-up analyses (t-tests) showed that the means of all levels of the factor cueing condition differed significantly from each other for each cue size (all $p \leq 0.01$).

4.3. Discussion

The pattern of results observed in Experiment 1 using filled-in cues was replicated in Experiment 3 using outline cues. Thus, low-level sensory factors such as sensory forward masking of the target by the cue do not seem to critically contribute to the main results we observed. This outcome complements the results of Experiments 1 and 2 and suggests that changes in attentional processes are responsible for the observed changes in size perception.

5. Experiment 4

The rationale behind the size variation of the exogenous cue relied on the assumption that the size of exogenous cues automatically adjusts the size of the attentional focus (see Introduction). Although this rationale and the corresponding procedure seems tried and tested (e.g., Greenwood & Parasuraman, 2004; Yeshurun & Carrasco, 2008), our case was even more compelling by demonstrating that changes of attentional foci by means of other than an exogenous cue affect perceived object size in a similar way. This was done in Experiment 4.

The design was similar to those used previously. We basically replaced the exogenous cue by a secondary task that induced either a small or a large attentional focus at a certain location with respect to the to be judged object (see Fig. 5). In a half of the trials, participants judged which of two circles presented laterally to a fixation cross is larger, as was done in Experiments 1 and 3. In the remaining trials a letter identification task was implemented. In particular, one group of the participants ("small focus group") was asked to report the identity of a letter shortly presented at the position of the center of one of the circles or below or above the fixation cross. Another group of the participants ("large focus group"), in contrast, had to attend to a group of four letters and to report the identity of the more frequent letter among these four. Before each block of trials, participants were informed about the region of the screen that was critical for the letter task. They were asked to attend to this region without moving their eyes (i.e. while keeping their gaze on the middle of the screen) and to report the corresponding letter presented in this region. The succession of the circle task and the letter task was unpredictable to the participant.

We thus used no explicit attention cues anymore, but varied the size of the attention focus by the attentional requirement of another task that occurred in trials other than the object judgement tasks. Consequently, in object judgment trials no cue that might potentially affect size judgments was present anymore. Specifically, during the presentation of the circles, the focus of attention in the small focus group should be at the position of the critical letter. That is it should encompass a small region of space which could coincide with the center of one of the circles or be at a neutral position. The attentional focus of the large focus group, in contrast, should be spatially more distributed around one of the circles or around one neutral position because at least two letters had to be simultaneously attended. Based on the results of the previous experiments, a small/large focus of attention was expected to increase/decrease the apparent size of the circle as compared with a neutral attention condition where the locations of circles and letters did not correspond

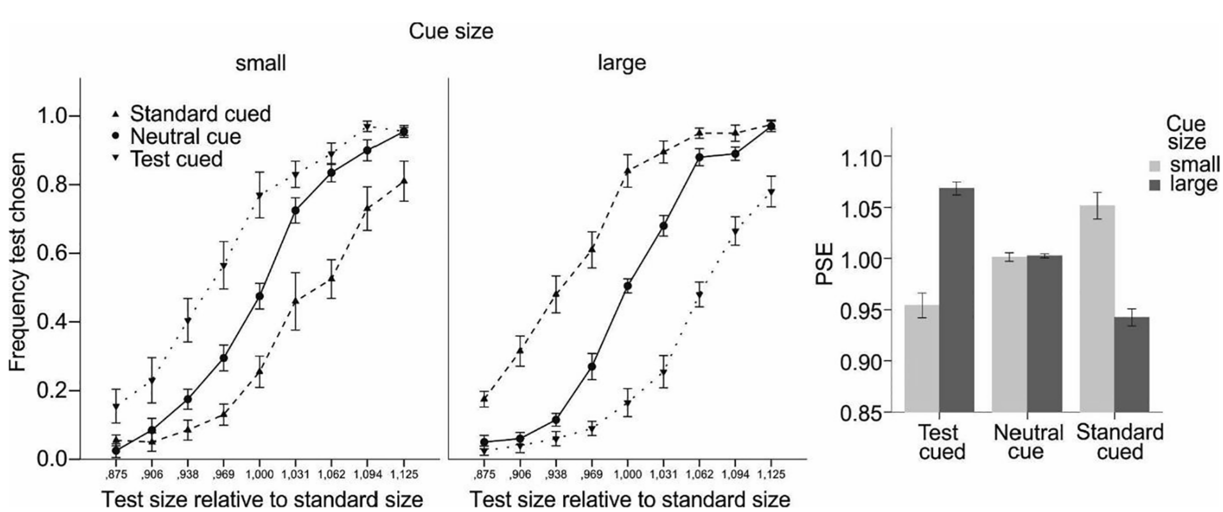

Fig. 4. Main results of Experiment 3. The percentage of trials for test cued, neutral and standard cued trials in which the test stimulus was judged as larger for the small and large cue. The according PSE values are on the right side of the figure. Error bars are standard errors.

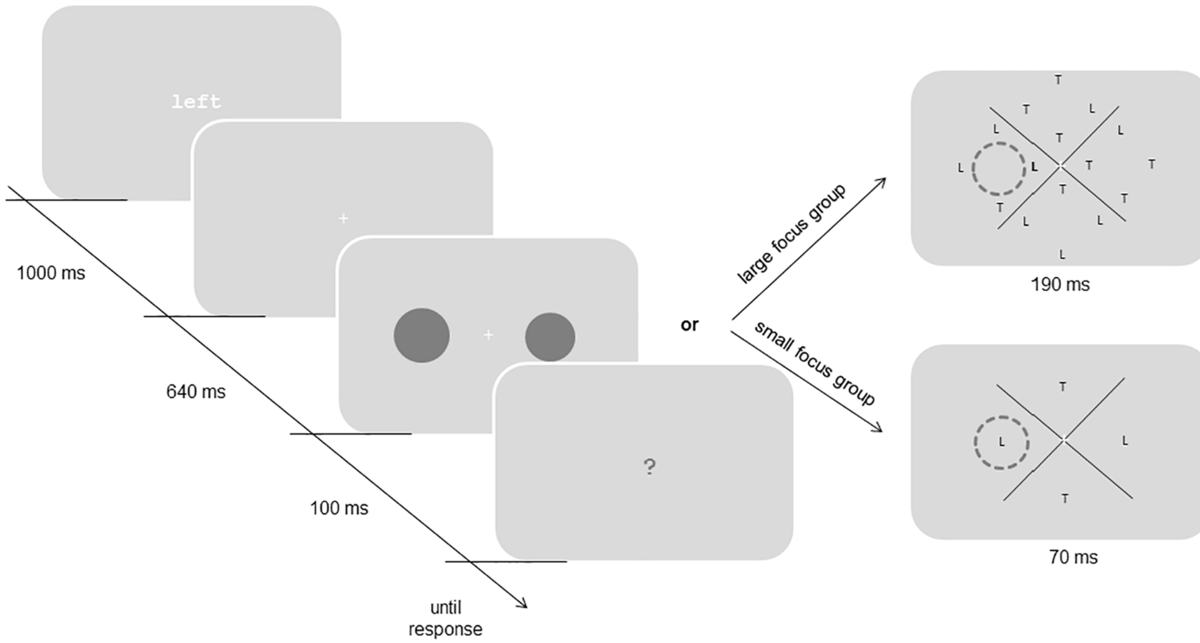

Fig. 5. The temporal structure of a single trial in Experiment 4 (not to scale). The dashed circles in the right part of the figure delineate the position of the left circle from the size judgment task.

5.1. Methods

5.1.1. Participants

Twenty-four participants were recruited[2]. None of them participated in Experiments 1–3. All were naive to the purpose of the experiment and had normal or corrected-to-normal vision. The sample included seventeen females and seven males ($M_{age} = 26$, $SD = 7$). Participants gave their written informed consent for the procedures and received either monetary compensation or course credit for their participation.

5.1.2. Apparatus

The apparatus was the same as in Experiment 1.

5.1.3. Stimuli

The stimuli were the same as in Experiment 1 with the following changes. Each trial now started with a cue word presented in the middle of the screen ("left", "right", "above" or "below" in German) and indicating to which part of the screen the participants should attend. The letters "L" and "T" were used as target stimuli additionally to the circles. Their color was black and their size was about 0.2°. The positions of the letters varied depending on the attentional focus condition. In the small focus condition, four letters were presented at 4° eccentricity left, right, above and below of the fixation cross. They were separated by two diagonal lines (black, 11° in length, and 0.03° in thickness). In the large focus condition, in contrast, four letters were presented at each part of the screen (see Fig. 5). These letters were positioned about 2° left, right, above or below of the letters' positions used in the small focus condition. That it, the positions of the lateral letters coincided with the centers of the circles in the small focus condition, and with the edges of the large cue used in the previous experiments in the large focus condition. The color of the question mark was maroon for the circle task and blue for the letter task.

5.1.4. Procedure and task

Participants were asked to keep their gaze on the middle of the screen and to shift their attention to the left or the right part of the screen, or above or below the fixation cross depending on the instruction presented bevor each block of trials and on the cue word presented in each trial. The cue word was presented for 1000 ms. Following 640 ms in which the fixation cross was shown either the circles or the letters were presented (unpredictably to the participant). In case of the circles, participants had to indicate which circle is larger by pressing the left or the right mouse button. When the letters appeared, the task was related to the identity of the letters. In the small focus condition, participants had to indicate which letter ("L" or "T") appeared at the location they were instructed to attend to. In the large focus condition, the task was to indicate whether more "Ls" or more "Ts" were presented at the attended part of the screen. The judgment was made using the arrow keys of the keyboard. The upper arrow key was assigned to the letter "L" and the lower arrow key to the letter "T". Both letters could appear with equal probability at each of the four positions in the small focus condition. In a similar vein, both letters could be less frequent and the less frequent letter could appear at one of the four positions within each of the four letter groups with equal probability in the large focus condition.

5.1.5. Design

As in the previous experiments one of the two circles was always the standard stimulus (2° in diameter), whereas the size of the other circle (test stimulus) varied from 87.5% to 112.5% of the standard diameter in nine steps. The standard and test stimuli could appear either left or right (unpredictably to the participant). The critical experimental variation of the size of attentional focus was implemented between the participants. That is, the half of the participants was assigned to the small focus condition, the other half to the large focus condition. The to be attended part of the screen (left, right, below, or above the fixation cross) varied from block to block but was constant across all trials in a single block. Analogously to the previous experiments this resulted in

[2] In contrast to Experiments 1–3, the sample included 5 left-handed and one ambidextrous participant. Three left-handers as well as the ambidextrous participant used their right hand to respond to the circle task and their left hand to respond to the letter task. Due to a small mistake of the experimenter this assignment was reversed for the other two lefthanders. We included handedness as a between-subject factor in the analyses presented below. No significant impact of this factor was observed indicating that handedness did not influence the results substantially.

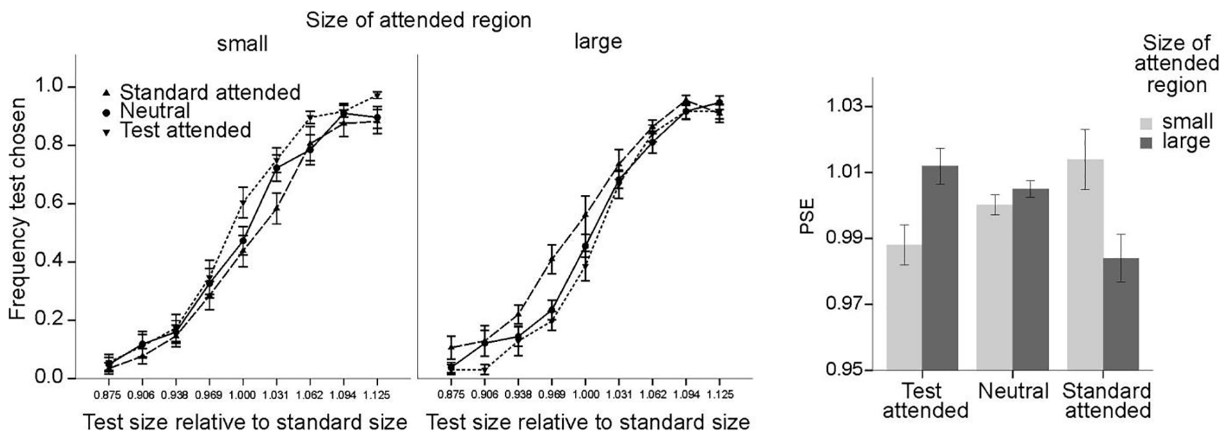

Fig. 6. Main results of Experiment 4. The percentage of trials for the test attended, neutral and standard attended conditions in which the test stimulus was judged as larger for the small (left part) and large (middle part) focus group. The according PSE values are on the right side of the figure. Error bars are standard errors.

three "cuing" conditions. When the left or the right part of the screen had to be attended either the standard circle or the test circle were attended. Attentional allocation above or below the fixation cross was treated as a neutral condition.

The main experiment included four blocks of trials with either 216 (attention left or right of the fixation) or 108 (attention above or below the fixation) trials each. In one half of the trials, the circles were presented. The other half included the secondary letter task. This resulted in 27 experimental conditions (size of the test stimulus (9) x "cuing" (3)), which were repeated 12 times for each focus group. Before the main experiment started participants performed 54 practice trials which were not included in the analysis.

5.1.6. Data analysis

The size judgments were analyzed in an analogous way as in Experiments 1 and 3. That is, we computed the proportion of trials in which the standard stimulus was attended, the test stimulus was attended, neutral positions were attended, and the test stimulus was judged as larger as a function of the test size. This was done for each participant. These values were then fitted with a psychometric function (mean $r^2 = 0.94$, $SD = 0.07$) and the point of subjective equality (PSE) was determined. The PSE values were then statistically analyzed.

5.2. Results

The performance of one participant in the secondary letter task was close to the chance level (47% of correct responses). His data was excluded from analyses. The performance of the small focus group in this task ($M = 82\%$, $SD = 9$) was overall better than of the large focus group ($M = 71\%$, $SD = 6$), $t(21) = 3.49$, $p = .002$.

Fig. 6 shows the mean judgment data (see Fig. S4 for individual data) as well as the results of the derived PSE measure. An ANOVA including focus size as a between-subjects factor, cuing condition (test attended, neutral, standard attended) as a within-subjects factor and the PSE values as a dependent variable revealed a significant interaction between both factors, $F(2, 42) = 7.48$, $p = .002$, $\eta_p^2 = 0.263$. We also run separate analyses (ANOVAs) for each focus group including cuing condition as a within-subjects factor. These analyses revealed a significant main effect of factor cuing for the large focus group, $F(2, 20) = 5.27$, $p = .015$, $\eta_p^2 = 0.345$ and a marginally significant main effect for the small focus group, $F(2, 22) = 2.92$, $p = .075$, $\eta_p^2 = 0.210$.

The standard attended condition differed significantly from the test attended condition, $t(10) = 2.26$, $p = .048$, as well as from the neutral condition, $t(10) = 3.11$, $p = .011$, for the large focus group. The test attended condition was not significantly different from the neutral condition, $t(10) = 1.05$, $p = .317$. For the small focus group, there were marginally significant differences between the test attended and the neutral conditions, $t(11) = 2.15$, $p = .055$, and between the test attended and the standard attended conditions, $t(11) = 1.81$, $p = .098$. The difference between the neutral and the standard attended condition was not significant, $t(11) = 1.33$, $p = .211$. Note, given the clear predictions one-tailed *t*-test would have been appropriate here, but for the sake of consistency we report the results of two-tailed t-tests.

The task we used in Experiment 4 could potentially be susceptible to eye movements. We made an attempt to prevent their possible impact by elaborate instructions. We also asked the participants whether they could follow the instructions at the end of the experiment. All participants confirmed that they could maintain the gaze in the middle of the screen in the majority of trials until the letters were presented[3]. Also note that a single eye movement strategy, such as anticipatory gazing towards the expected letter position, cannot explain the observed pattern of results due to the opposite effect directions for the small and large focus groups.

5.3. Discussion

Experiment 4 examined whether the observed changes in apparent object's size induced by exogenous attentional cues of varying size can be observed without any cues preceding the critical object. We encouraged the participants to focus their attention either on a single object or on a group of spatially distributed objects by means of an interspersed perceptual identification task. Judgments of objects' size were affected by this manipulation in an analogous way as by the exogenous cues used in the previous experiments. That is, when attention was focused at a small region of space located at the center of an object that object was judged to be larger as compared with a neutral attention condition, and conversely, with a more spatially distributed focus a decrease in estimated size was observed. The effects were smaller in magnitude in Experiment 4 than in the previous experiments, possibly because exogenous cues induce stronger and temporally more confined changes of attention as compared to the perhaps weaker but more sustained changes of attention induced by another task. Still, the pattern of results clearly corroborates the conclusion that the size of the attentional focus modulates the apparent size of objects.

[3] One participant from the small focus group stated that she tried to move her gaze to the letters as soon as the letters were presented. Such a strategy can be assumed to be not critical because the circle task would be unaffected. Also the letter task could not profit from it due to a short duration of letter presentation (70 ms). We thus did not exclude this participant from the analyses.

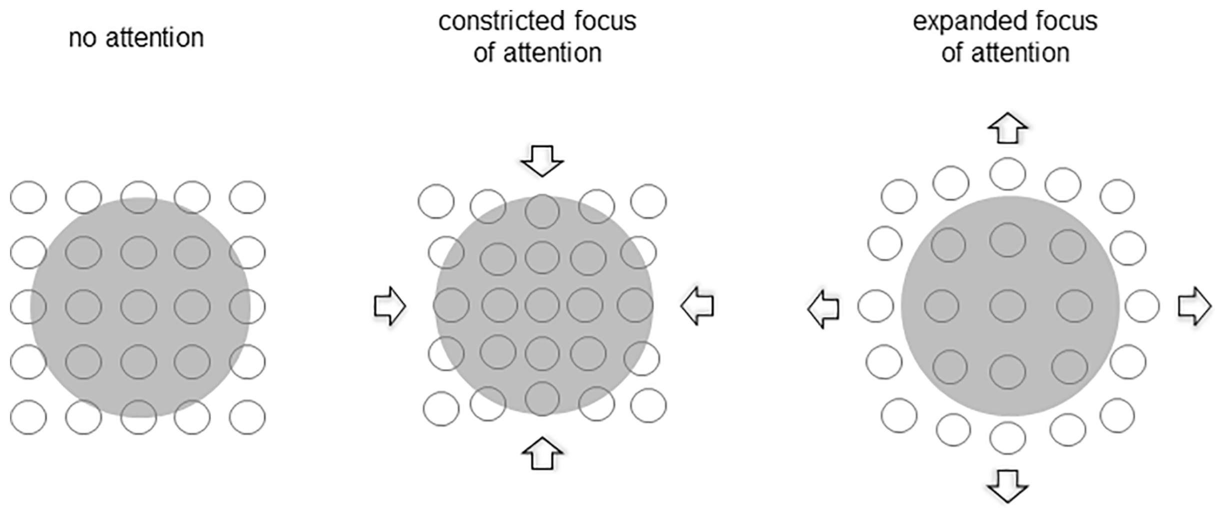

Fig. 7. Assumed relation between the size of the attended region and the perceived size of an object (filled circle). The small circles denote a grid of RFs of afferent cortical neurons. The left panel of the figure depicts a situation where no attention is specifically directed towards the object (Please note that the depicted grid of RFs outlines an idealized situation where attention is not allocated to any spatial location or it is equally distributed across all possible locations (including the relevant object location). This does not necessarily imply that attention was distributed in this way in the neutral conditions of the present study. For example, RFs could have been attracted by the neutral (i.e. central) cue location in Exp.1–3 to some extent. Such possible "baseline" effects, however, are in our view not critical for the explanation of the observed changes in size perception with the size of attentional focus depicted in the middle and right parts of Fig. 7.). In the middle panel, attention is drawn to the object's center. As a result, RFs shift towards the attended region, i.e. to object's center (indicated by arrows). In the right panel, attentional resources are distributed over a large region of space encompassing the object and beyond. We suggest that this entails a shift of RFs away from the object's center. Because more distant RFs are activated by the stimulus with the constricted attentional focus than with "no attention" the stimulus appears larger. And conversely, because the object no longer stimulates some of the distant RFs with an expanded focus as compared with "no attention", the stimulus appears smaller in the former than in the latter case.

6. General discussion

We examined how changes in spatial attention alter the way in which objects subjectively appear. We varied the size of attentional cues and tested the impact of this manipulation on the perceived size of objects in Experiments 1–3. Very consistently, small cues increased reported object's size (Exp. 1), as shown before (Anton-Erxleben et al., 2007). In contrast, large cues, equally consistently, affected reported object size in an opposite manner. That is, objects were judged as smaller. A control experiment (Exp. 2) indicated that the observed effects are due to changes in perception rather than due to response biases. Also, changes in attention rather than low-level sensory interactions between the cue and the target appear responsible for the effects we observed (Exp. 3). Moreover, equivalent findings were observed with endogenous changes in the size of attentional focus in the absence of any exogenous cues (Exp. 4). These results suggest that the size of the attended area determines the appearance of objects. If attention is focused at a small central region of an object then that object appears larger (as compared with a neutral attention condition). An expanded focus, in contrast, lets the target appear smaller.

The original finding of an increase of perceived object's size with attention allocated at the center of the object (Anton-Erxleben et al., 2007) was ascribed to changes in the position of receptive fields (RF) near the attended location (Anton-Erxleben & Carrasco, 2013; Anton-Erxleben et al., 2007; Baruch & Yeshurun, 2014; see also Suzuki & Cavanagh, 1997 for a similar explanation of the ARE). According to this approach, an increase in perceived object's size is mediated by a shift of the RFs towards the focus of attention (see Fig. 7, left and middle parts). Some of the RFs which are outside of an object without attention move "inside" the object with an attentional shift. As a result, the object now activates RFs of neurons which originally coded more distant positions. Assuming that RFs are still labelled with their original position the object is perceptually magnified.

According to the Attentional Attraction Theory (Baruch & Yeshurun, 2014), such an attraction of RFs towards the attended location is susceptible to the size of the attentional focus: a wider focus should decrease the perceived size as compared with a narrow focus due to a smaller RF-shift. At this point, our results are in line with this and similar accounts. However, we observed that the large focus decreased the perceived object's size also in comparison to a neutral condition in which the critical object was not specifically attended. None of the previous models would currently predict this finding to our knowledge.

Here, we suggest that a drift of the RFs away from the center of attentional focus can explain this result (see Fig. 7, left and right parts). Such a drift would entail that the critical object no longer stimulates some of the RFs with an expanded focus as compared with a neutral condition. As a consequence, the object would appear smaller according to the logic outlined above.

This assumption would imply that an RF-shift towards the center of attention is a special case of a more general mechanism adjusting attentional resources according to given task requirements. When fine details have to be resolved at a certain spatial location it might be reasonable to allocate more RFs at this location. This enhancement of spatial resolution can well be explained and modelled by RF-shift towards the center of attention (Baruch & Yeshurun, 2014, see also Introduction). There are, however, situations in which it is not reasonable to resolve fine object details. Under such conditions, it might be more advantageous to decrease the spatial resolution (e.g., Balz & Hock, 1997; Eriksen and St. James, 1986; Greenwood & Parasuraman, 2004; Goto, Toriu, & Tanahashi, 2001) and this can be achieved, at least in theory, by shifting RFs away from the center of attentional focus. As a practical consequence of such a mechanism we might overlook an apparently small bison grazing at the edge of a forest while first attending the whole forest, but possibly become frightened by the apparently enlarged bison when focusing a bush close to this animal.

These conclusions are of course preliminary. Whereas the attraction of RFs towards the attended location is physiologically well supported (e.g., Womelsdorf, Anton-Erxleben, Pieper, & Treue, 2006), the possible existence of RF shifts in the opposite direction (i.e., away from the center of attention) is an open question. Also, we cannot refute all possible alternative explanations so far. For example, Exp. 2 did exclude an impact of a simple response bias such as preferring or avoiding the cued location. However, a possible impact of more complex biases cannot be completely ruled out (cf. Kerzel et al., 2010). For example, participants could associate the cued stimulus with “more” (large cue) or “less” (small cue) along a quantitative dimension (e.g., size). As a result, a type of repulsion effect between the size of the cue and the size of the target could emerge. Such an effect could, in theory, be also perceptual in nature (i.e., related to changes in the perception of target size), being however unrelated to attention. This and related issues need further investigation.

Our original motivation of the present study rooted in the research on the impact of action on spatial perception. Several studies indicated that motor skills correlate with the perceptual judgments of skill-related objects such as of goals or balls (e.g., Witt, Linkenauger, Bakdash, & Proffitt, 2008; Cañal-Bruland & van der Kamp, 2009). For example, the (anticipated) ability to hit a target correlated with judgments of target size in archery (Lee, Lee, Carello, & Turvey, 2012). Usually an increase in motor performance is associated with an increase in apparent target size. We supposed that these and similar observations are due to changes in the size of the attentional focus accompanying changes in motor ability (p. 1762 in Kirsch, Königstein, & Kunde, 2014; cf. also Kirsch, 2015). The present results are well in line with this claim. In particular, one way to increase performance in such tasks is to focus more attention at the center of the target. This would increase the spatial resolution of the central target area as well as the apparent target size as outlined above.

To conclude, the present results suggest that the previously observed increase in the apparent size of an attended object is not due to attentional allocation per se but due to a small focus of attention. This finding indicates that the impact of attention on objects’ appearance strongly depends on the size of the attended spatial area. Accordingly, other related effects observed using small foci of attention, such as the ARE, might be rather special cases of a general mechanism adjusting attentional resolution to current task requirements.

Acknowledgments

This research was supported by grant KI 1620/1-2 awarded to W. Kirsch by the German Research Council (DFG).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.visres.2018.10.004.

References

Anton-Erxleben, K., Abrams, J., & Carrasco, M. (2011). Equality judgments cannot distiguish between attention effects on appearance and criterion: A reply to Schneider (2011). *Journal of Vision, 11*(13), 1–8.

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., Heinrich, C., & Treue, S. (2007). Attention changes perceived size of moving visual patterns. *Journal of Vision, 7*(11), 1–9.

Balz, G. W., & Hock, H. (1997). The effect of attentional spread on spatial resolution. *Vision Research, 37*(11), 1499–1510.

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

Cañal-Bruland, R., & van der Kamp, J. (2009). Action goals influence action-specific perception. *Psychonomic Bulletin and Review, 16*(6), 1100–1105.

Carrasco, M., & Barbot, A. (2015). How attention affects spatial resolution. *Cold Spring Harbor Symposia on Quantitative Biology*. https://doi.org/10.1101/sqb.2014.79.024687.

Carrasco, M., Ling, S., & Read, S. (2004). Attention alters appearance. *Nature Neuroscience, 7*(3), 308–313.

Castiello, U., & Umilta, C. (1990). Size of the attentional focus and efficiency of processing. *Acta Psychologica, 73*, 195–209.

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

Fortenbaugh, F. C., Prinzmetal, W., & Robertson, L. C. (2011). Rapid changes in visual-spatial attention distort object shape. *Psychonomic Bulletin and Review, 18*, 287–294.

Fuller, S., & Carrasco, M. (2006). Exogenous attention and color perception. Performance and appearance of saturation and hue. *Vision Research, 46*, 4032–4047.

Gobell, J., & Carrasco, M. (2005). Attention alters the appearance of spatial frequency and gape size. *Psychological Science, 16*, 644–651.

Golla, H., Ignashchenkova, A., Haarmeier, T., & Thier, P. (2004). Improvement of visual acuity by spatial cueing: A comparative study in human and non-human primates. *Vision Research, 44*, 1589–1600.

Goto, M., Toriu, T., & Tanahashi, J. (2001). Effect of size of attended area on contrast sensitivity function. *Vision Research, 41*, 1483–1487.

Greenwood, P. M., & Parasuraman, R. (2004). The scaling of spatial attention in visual search and its modification in healthy aging. *Perception and Psychophysics, 66*(1), 3–22.

Hock, S. H., Balz, G. W., & Smollon, W. (1998). Attentional control of spatial scale: Effects on self-organized motion patterns. *Vision Research, 38*, 3743–3758.

Kerzel, D., Zarian, L., Gauch, A., & Buetti, S. (2010). Large effects of peripheral cues on appearance correlate with low precision. *Journal of Vision, 10*(11), 1–14.

Kirsch, W. (2015). Impact of action planning on spatial perception: Attention matters. *Acta Psychologica, 156*, 22–31.

Kirsch, W., Königstein, E., & Kunde, W. (2014). Hitting ability and perception of object's size: Evidence for a negative relation. *Attention, Perception, and Psychophysics, 76*, 1752–1764.

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), 1–13.

Lee, Y., Lee, S., Carello, C., & Turvey, M. T. (2012). An archer’s perceived form scales the “hitableness” of archery targets. *Journal of Experimental Psychology: Human Perception and Performance, 38*(5), 1125–1131.

Prinzmetal, W., Long, V., & Leonhardt, J. (2008). Involuntary attention and brightness contrast. *Perception and Psychophysics, 70*(7), 1139–1150.

Schneider, K. A. (2011). Attention alters decision criteria but not appearance: A reanalysis of Anton-Erxleben, Abrams, and Carrasco (2010). *Journal of Vision, 11*(13), 1–8.

Schneider, K. A., & Komlos, M. (2008). Attention biases decisions but not alter appearance. *Journal of Vision, 8*(15), 1–10.

Shulman, G. L. (1992). Attentional modulation of size contrast. *The Quarterly Journal of Experimental Psychology, 45A*(4), 529–546.

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.

Witt, J. K., Linkenauger, S. A., Bakdash, J. Z., & Proffitt, D. R. (2008). Putting to a bigger hole: Golf performance relates to perceived size. *Psychonomic Bulletin and Review, 15*(3), 581–585.

Womelsdorf, T., Anton-Erxleben, K., Pieper, F., & Treue, S. (2006). Dynamic shifts of visual receptive fields in cortical area MT by spatial attention. *Nature Neuroscience, 9*(9), 1156–1160.

Yeshurun, Y., & Carrasco, M. (2008). The effects of transient attention on spatial resolution and the size of the attentional cue. *Perception and Psychophysics, 70*(1), 104–113.

Zychaluk, K., & Foster, D. H. (2009). Model-free estimation of the psychometric function. *Attention, Perception and Psychophysics, 71*, 1414–1425. https://doi.org/10.3758/APP.71.6.1414.