

Mean size estimation yields left-side bias: Role of attention on perceptual averaging

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Abstract The human visual system can estimate mean size of a set of items effectively; however, little is known about whether information on each visual field contributes equally to the mean size estimation. In this study, we examined whether a left-side bias (LSB)—perceptual judgment tends to depend more heavily on left visual field’s inputs—affects mean size estimation. Participants were instructed to estimate the mean size of 16 spots. In half of the trials, the mean size of the spots on the left side was larger than that on the right side (the left-larger condition) and vice versa (the right-larger condition). Our results illustrated an LSB: A larger estimated mean size was found in the left-larger condition than in the right-larger condition (Experiment 1), and the LSB vanished when participants’ attention was effectively cued to the right side (Experiment 2b). Furthermore, the magnitude of LSB increased with stimulus-onset asynchrony (SOA), when spots on the left side were presented earlier than the right side. In contrast, the LSB vanished and then induced a reversed effect with SOA when spots on the right side were presented earlier (Experiment 3). This study offers the first piece of evidence suggesting that LSB does have a significant influence on mean size estimation of a group of items, which is induced by a leftward attentional bias that enhances the prior entry effect on the left side.

Keywords Summary statistics · Visual perception · Attention · Cueing · Prior entry

Perceptual averaging

When perceiving numerous external inputs at once in our visual worlds, our perceptual system has an efficient way to represent similar objects (e.g., leaves on a tree, people in a mall) collectively using summary statistics (see Haberman & Whitney, 2012, for review). Indeed, previous studies have demonstrated that our perceptual system has a fascinating ability to estimate the mean properties of a group of multiple items, such as the mean size (Albrecht & Scholl, 2010; Ariely, 2001; Chong & Treisman, 2003, 2005b), direction, and moving speed (Emmanouil & Treisman, 2008). In addition to these low-level features, high-level properties (e.g., average emotion or gender of a group of people) can also be estimated, even when individual items are difficult to identify (Haberman & Whitney, 2007).

In the current study, we focused on mean size of a group of items, which can be estimated by our perceptual system despite items’ arrangement or duration variations (Albrecht & Scholl, 2010; Ariely, 2001; Chong & Treisman, 2003, 2005b). Ariely (2001) offered the first piece of relevant evidence by asking participants to perform a member-identification task (i.e., judging whether the test spot belonged to the set or not) and a mean discrimination task (i.e., judging whether the test spot was smaller or larger than the mean size of the set) after presenting the participants with a set of different-sized spots. The results showed that, although participants could not identify whether the test spots belonged to the set or not, they could actually estimate the mean size, regardless of the number of the spots. Later studies expanded this finding and found that the mean size estimation ability was independent of the

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spots' number, density, and distribution (Chong & Treisman, 2003, 2005b). Furthermore, this ability persists even when the group of spots was only presented for 50 ms (Chong & Treisman, 2003) and when each spot was presented sequentially (Albrecht & Scholl, 2010).

The left-side bias

Such mean size estimation often involves judgment of a group of stimuli presented on both sides of visual fields. Thus, an interesting question arises: Does the information on each side contribute equally to the mean size estimation? Previous studies suggest that people have a tendency to rely more heavily on inputs from the left visual field, called the left-side bias (LSB). For example, Gilbert and Bakan (1973) presented an original face, a left-mirrored face (i.e., composed of the left side of the original face, which was from the viewers' sight hereafter and its mirrored image), and a right-mirrored face (i.e., created using the right side of the original face and its mirrored image), and asked participants to judge which chimeric face seems more similar to the original face; they reported that participants judged the left-mirrored face to be more similar to the original face than the right-mirrored face. Delving deeper, Burt and Perrett (1997) further revealed that the LSB also occurred when judging other dimensions of the face, including gender, age, expression, and attractiveness. Along the same line, Butler et al. (2005) found a leftward-focused eye-movement pattern (with more saccades and longer fixations) when individuals were observing chimeric faces. Moreover, in addition to face perception, the LSB was also shown in other perceptual tasks. For example, Nicholls, Bradshaw, and Mattingley (1999) asked participants to compare the brightness, numerosity, and size of a bar with its mirror image. They found that participants' judgments were mainly based on the target feature on the left half of the bar. In summary, there seems to be a stronger preference for information coming from the left visual field.

Nicholls and Roberts (2002) proposed three possible mechanisms to account for the LSB: the left-to-right scanning bias, the premotor activation, and the hemispatial attentional bias. The left-to-right scanning bias refers to that the left portion of the stimuli is overrepresented than the right portion because participants' habit of scanning the text from the left to the right in reading. The premotor activation hypothesis suggests that the LSB results from unilateral motor activation on the right hemisphere, and thus the LSB may be stronger when participants respond with their left hand. The hemispatial attentional bias suggests that the LSB results from an automatic attention shift toward the left side. Nicholls and Roberts (2002) directly examined these three accounts with three manipulations. First, they recruited Hebrew readers, who read and scan the text from right to left, and English readers,

who read and scan the text from left to right, to examine the influence of scanning bias. Second, participants were asked to respond using both hands simultaneously in order to exclude the possibility of premotor activation account. Finally, they used a cue to direct participants' attention to the left or the right side to investigate the effect of hemispatial attentional bias. Through these three manipulations, they found that both Hebrew and English readers displayed the LSB while bisecting a line or comparing the brightness of two bars, and the magnitude of the LSB was reduced when attention was cued to the right side. Accordingly, they favored the hemispatial attentional bias account over the other two accounts of the LSB.

Attention modulation on mean size estimation and its relation with the LSB: Equal or unequal distribution?

Previous studies have shown that mean size estimation can be modulated by attention. Chong and Treisman (2005a) asked participants to estimate the mean size with a concurrent task (e.g., finding *O* in a group of *C*s or finding *C* in a group of *O*s), and found that statistical processing was better when the concurrent task required distributed (or global) attention than when it required focused (or local) attention. De Fockert and Marchant (2008) further illustrated that attended items (compared to unattended ones) contributed more to the mean size estimation. In their study, a set of circles was presented, followed by two test circles. One of the test circles was either larger or smaller than the mean size of the previous set of circles, and the other had the same size as the set mean. Participants were asked to report the location of either the smallest or the largest circle based on cue instruction during the presentation of the set of circles and then judge which one of the two test circles had the same size as the set mean during the test circles phase. They found that the participants were more likely to choose the test circle with the size closer to the circle they attended to during the presentation of the set of circles, regardless of whether it was the actual mean size.

It thus seems that the pattern of attention distribution would influence the mean size estimation, as inferred from the abovementioned studies (Chong & Treisman, 2005a; De Fockert & Marchant, 2008). Accordingly, two distinct hypotheses on the occurrence of the LSB in mean size estimation are proposed here: the equal attention distribution hypothesis and the unequal attention distribution hypothesis. In both hypotheses, we assume that when estimating the mean size, people would distribute their attention to all items, and the only difference between the two hypotheses is the pattern of distribution. In the equal distribution hypothesis, all items receive the equal amount of attention, and the LSB would not occur on mean size estimation. In the unequal distribution hypothesis,

some portions of the stimuli receive more attention than others. If people inherently distribute more attention to the stimuli on the left side, then it would in turn yield the LSB. This unequal distribution attention hypothesis is in line with the finding of Nicholls and Roberts (2002), although they used single objects rather than a group of items.

In fact, the hemispatial attentional bias hypothesis in Nicholls and Roberts (2002) is supported by studies on holistic processing, which showed a right-hemisphere advantage (Christie et al., 2012; Martinez et al., 1997; Yovel, Yovel, & Levy, 2001). Past research using hierarchical figures (e.g., small *H*s grouped together to form a large or holistic letter *E*) to test participants' detection at global versus local levels found that participants were able to detect the holistic shape faster and more accurately when the hierarchical figure was presented on the left visual field (Christie et al., 2012; Yovel et al., 2001). Such right-hemisphere advantage was also found in an fMRI study (Martinez et al., 1997): When participants attended to the holistic shape (i.e., distributed attention over the whole shape), the right hemisphere displayed greater brain activation than the left hemisphere. Because mean size estimation is also a type of holistic processing, it is possible that items presented on the left visual field would have greater contribution in the overall mean size estimation based on that hemispheric advantage. However, considering that the two tasks Nicholls and Roberts (2002) used (i.e., the line bisection task and the luminance comparison task) involved only single objects, it remains speculative whether the effect of LSB on statistic perception that involves a group of items would be obtained, and if so, is also due to attentional bias toward the left side.

Goal of this study

In the present study, we hypothesize that mean size estimation may yield LSB. Specifically, when people estimate the mean size of multiple items across the two visual fields, we predict that items in the left visual field would weight more than items in the right visual field due to the left-side attentional bias. In other words, the estimated overall mean size should be closer to the actual mean size of items in the left visual field. In order to test our hypothesis, we adopted a simple mean size adjustment task in which a set of spots were presented on the screen and equally distributed on the left and the right side. In order to manifest the LSB, the mean size of the spots on the left and the right side was controlled so that, in some cases, the left side spots have larger mean size than the right side spots, and vice versa. Experiment 1 examined the occurrence of the LSB when estimating the mean size of the entire set of spots. After demonstrating the occurrence of the LSB, the following two experiments further explored the underlying mechanism of the LSB by directing

participants' attention to the left or the right side (Experiment 2) and manipulating the stimulus-onset asynchrony (SOA) between the spots on each side to examine if prior entry of attention contributes to the LSB (Experiment 3).

Experiment 1

In the first experiment, the occurrence of the LSB during mean size estimation was examined using the mean size adjustment task. In each trial, a set of spots with various sizes was presented and equally assigned to the left and the right side of the screen. The mean size of the spots on each side was manipulated: it was either larger on the left side (i.e., the Left-larger condition) or larger on the right side (i.e., the Right-larger condition). Following the display of the spots, a central test spot was presented, and participants were asked to adjust the size of the test spot into the perceived mean size of the target set. Eye movements were monitored during the presentation of the set of spots, and participants were constrained to keep their eyes focused on the central fixation points in order to ensure that the retinal eccentricities of the spots on both sides were similar. If the estimated mean size is larger in the left-larger condition than in the right-larger condition, then it suggests that mean size estimation is affected by the LSB. In contrast, if there is no LSB on mean size estimation, then the estimated mean size should be the same in both conditions.

Method

Participants Twenty-four participants (two left-handed and six left-eye-dominant)¹ were recruited. All participants gave informed consent and were compensated for their participation. All of them had normal or corrected-to-normal vision and were naïve to the purpose of the experiment until the end of the experiment. This study was approved by the Research Ethics Committee at National Taiwan University.

Apparatus and stimuli All stimuli were presented on a black screen of an i-TECH 20-in. CRT monitor with a spatial resolution of 1024 × 768 pixels at 120-Hz refresh rate. A chin rest was used to reduce participants' head movement. Each participant performed the task individually in a dim room while they

¹ In this study, the number of participants was determined by a priori power analysis with G*Power software (University of Dusseldorf, Germany) based on the effect size ($\eta_p^2 = .263$) of a pilot experiment with seven participants. The analysis revealed that 25 participants were needed to reach the significance level of .05 and statistical power of 0.8. According to this analysis, as well as the counterbalanced design in Experiment 2b and our plan to compare the results across the experiments, 24 participants were recruited for all experiments in this study.

were seated at about 65 cm in front of the computer screen. At this distance, a pixel takes up about 0.023° of visual angle.

Each trial consisted of three frames: a fixation cross, a set of spots, and a central test spot. The fixation cross was a white cross (RGB: 255, 255, 255) located at the center of the screen and subtended $0.62^\circ \times 0.62^\circ$. The set of spots was composed of 16 white filled spots (RGB: 255, 255, 255) with various sizes, and the mean size of the entire set was randomly selected from the five sizes ($1.23^\circ \times 1.23^\circ$, $1.41^\circ \times 1.41^\circ$, $1.60^\circ \times 1.60^\circ$, $1.86^\circ \times 1.86^\circ$, and $2.08^\circ \times 2.08^\circ$) for each trial. The mean size of each side and the size of each spot were determined by the following steps: (1) The overall or whole mean size (M_W) was multiplied by 0.75 and 1.25. The two values ($0.75M_W$ and $1.25M_W$) were then assigned as the mean size of spots on the right side (M_R) and the left side (M_L), respectively. (2) A modulation value was randomly picked from the range of 0.1 ~ 0.3 (except for 0.25), and each step was 0.01. (3) M_R was multiplied by the 1+ modulation value and 1–modulation value, respectively, in order to generate two values for the spots on the right side (e.g., if modulation value was 0.15, the two generated values would be $1.15 M_R$ and $0.85 M_R$). (4) The second and third steps were repeated four times to generate a total of eight values that composed the sizes of the spots on the right side. (5) Steps two, three, and four were repeated with M_L instead of M_R to generate the sizes of spots on the left side. (6) A total of 16 values (eight for each side) were generated. The 16 values were set as the sizes of spots in one trial and the same value of each side would be reassigned to the opposite side in the other trial. The sizes of the spots ranged from $0.89^\circ \times 0.89^\circ$ to $2.65^\circ \times 2.65^\circ$. The test spot was a white spot (RGB: 255, 255, 255) that ranged from $0.84^\circ \times 0.84^\circ$ to $2.75^\circ \times 2.75^\circ$ and was randomly chosen for each trial. None of these spots had the same size as M_W , M_L , or M_R .

All of the spots were placed in two imaginary squares. Both squares subtended $8.34^\circ \times 12.89^\circ$ and were located 4.47° from the fixation point to the left and the right side of the screen, respectively. Each square was divided into a 2×4 matrix. The spots on each side were randomly assigned to one of the eight cells and were randomly jittered within the range of 0.12° in the cells. The distance between the spots ranged from 2.16° to 3.96° between the two sides and from 0.39° to 3.53° within the same side. The test spot was presented at the center of the screen.

Eye-movement monitoring To ensure that participants were fixating at the center of the screen during the presentation of the set of spots, participants' eye movements were monitored by an EYELINK 2000 eye tracker (SR Research, Mississauga, Ontario, Canada). The standard five-points calibration and validation procedure were administered before the experiment, and the eye tracker tracked the movements of participants' dominant eye with a sampling rate of 1000 Hz. During the presentation of the spots, if the eye tracker detected

a gaze 1.5° away from the fixation cross, the experiment would suspend and all stimuli, except that the fixation cross would disappear until the gaze returned to the fixation cross. When the experiment was suspended, the fixation cross would turn bright blue (RGB: 128, 128, 255) to remind participants to refixate on the fixation cross, and the trials without fixations would be skipped and rerun at the end of the block. If the experiment still suspended after participants tried to refixate on the fixation cross, the calibration and validation procedure of eye movements was adopted to refine the precision of the eye tracker, and the trial during calibration and validation would be excluded from further analysis. Participants were well informed about the procedures before the experiment.

Design A one-factor (mean size difference: left-larger, right-larger) within-subjects design was adopted. In the left-larger condition, M_L was 60% larger than M_R , and vice versa. Each condition contained 80 trials, resulting in 160 trials total.

Two dependent variables were calculated (see the formula below): first, in order to reveal the LSB, the direction of the estimation error was more important than the magnitude of the estimation error. In other words, it was more important to know if the estimated mean size was larger in the left-larger condition and smaller in the right-larger condition rather than knowing which condition has the larger estimation error. Accordingly, we calculated the relative mean size difference (RMSD), which was defined as the difference between the size that participants estimated and the actual M_W divided by actual M_W ; second, the absolute mean size difference (AMSD), which was defined by the absolute value of RMSD, was calculated to screen out the outliers of the performance:

$$\text{RMSD} = \frac{\text{Estimated mean size} - \text{Actual } M_W}{\text{Actual } M_W}$$

$$\text{AMSD} = |\text{RMSD}|$$

Procedure Before entering the experiment, a practice phase with 12 trials (six trials for each condition) was conducted for the participant to familiarize the procedure of the experiment. The experiment contained four blocks, and each block had 40 trials (20 trials per condition). A rest period was interleaved between each block, and participants pressed the space bar to initiate each block.

The procedure of each trial is illustrated in Fig. 1. Each trial began with a central fixation cross (jittered from 1,000 to 1,200 ms), and then the set of spots was presented for 100 ms, followed by the presentation of a central test spot until participants responded. Participants were asked to adjust the size of the test spot as accurately as possible until it appeared to be the same as M_W by scrolling the mouse wheel (the minimum step of an adjustment was 1 pixel). After the

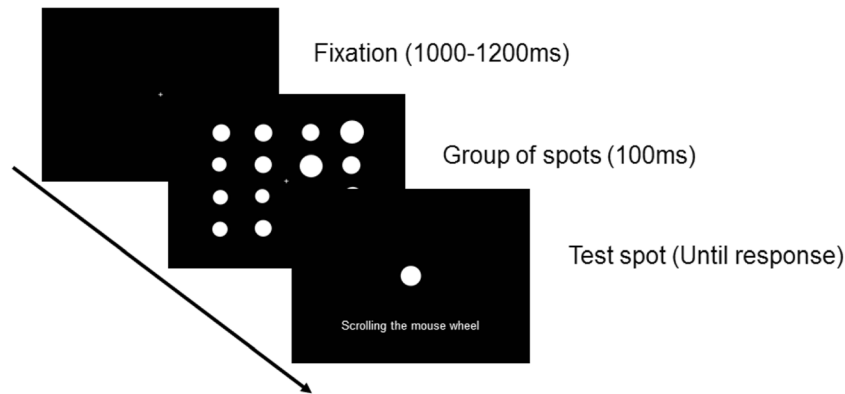


Fig. 1 Procedure of each trial in Experiment 1. A group of spots was presented for 100 ms. In half of the trials, the mean size of spots on the left side was larger than that on the right side (left-larger condition) and the situation reversed in the remaining trials (right-larger condition, as shown

in this example). Following the display of the spots, a test spot was presented, and participants were asked to adjust the test spot to be the same as the mean size of the whole group of spots (i.e., M_W)

adjustment, participants submitted their answer by pressing the space bar, which also initialized the next trial. In order to prevent any possible confounding factor from the setting of the device and motor response, the mouse and keyboard were aligned with the center of the monitor, and participants were asked to use their right hand to control the mouse and use their left hand to press the space bar.

Results

The data were filtered by two criteria for each participant. First, the trials where participants lost their fixation and need to refine the precision of the eye tracker were excluded from further analysis. Second, the trials that the AMSD exceeded or lower than two standard deviations of the mean AMSD were excluded as well. According to these two criteria, 4.27% of the trials were excluded.

The mean RMSD of the remaining data was presented in Fig. 2, and two analyses were conducted on the RMSD data. First, in order to ensure that participants actually made an effort to average the sizes of the spots without random guesses, a one-way (M_W : $1.23^\circ \times 1.23^\circ$, $1.41^\circ \times 1.41^\circ$, $1.60^\circ \times 1.60^\circ$, $1.86^\circ \times 1.86^\circ$, and $2.08^\circ \times 2.08^\circ$) repeated-measures ANOVA was conducted on the RMSD data. Here, the variance of the sizes between the spots was increased with the M_W due to the generated method we used (as described at the Apparatus and Stimuli section). We assumed that if participants actually averaged the sizes of the spots, the variance between the spots would influence the estimation, and the RMSD would increase with M_W . In contrast, if participants just randomly picked a spot to report, the variance between the spots would have no impact on the estimation, and the RMSD

would be the same across the five M_W . As demonstrated in Fig. 2a, the ANOVA showed a significant linear trend, $F(1, 23) = 19.41$, $p < .01$, $\eta_p^2 = .46$, suggesting that the RMSD actually increased with the M_W , and participants indeed averaged the sizes of the spots.

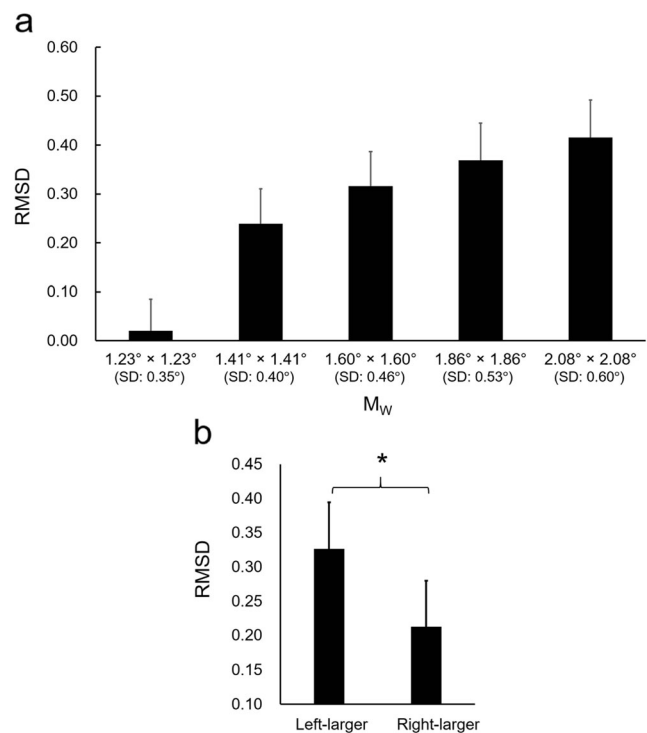


Fig. 2 Results of Experiment 1. a The average RMSD across the five M_W 's. b The average RMSDs of the two conditions in Experiment 1. The black line above each bar refers to the standard error of the mean for each condition. M_W = the mean size of the whole group spots; RMSD = relative mean size difference; SD = standard deviation of the spot size in each M_W condition; * $p < .05$

Second, to examine the LSB, we analyzed the data using a one-way (mean size difference: left-larger, right-larger) repeated-measures ANOVA. As shown in Fig. 2b, the ANOVA indicated that the main effect of mean size difference, $F(1, 23) = 6.50$, $p < .05$, $\eta_p^2 = .22$, was significant. The RMSD was larger in the left-larger condition than in the right-larger condition (0.33% vs. 0.21%).

Discussion

The results of Experiment 1 were consistent with previous studies that the variance among the set of stimuli can influence the performance of ensemble averaging—the performance of estimation deteriorates with the increasing variance among the set of stimuli (Dakin, 2001; Dakin, Bex, Cass & Watt, 2009; Im, & Halberda, 2013)—and suggested that participants indeed averaged the size during even a very brief exposure duration (100 ms).

More important, our results demonstrated an LSB on mean size estimation: The estimated mean size was indeed larger when the left side contained the spots with larger mean size than the reversed situation. However, because the variation of spot size was always accompanied with the variation of luminance (e.g., larger mean size of the spots was always accompanied with higher mean luminance), it could be the case that participants estimated the mean luminance rather than the mean size. This possibility was investigated in the next experiment.

Experiment 2a

Having established the LSB on the mean size estimation in Experiment 1, we went one step further in Experiment 2 to explore the role of attention on LSB while also taking the possible confounding of mean luminance into consideration. In Experiment 2a, two issues—the possibility of mean luminance (rather than mean size) estimation and the role of attention on LSB we found in Experiment 1—were addressed by two changes of stimuli here. The spots were replaced by outline circles in order to minimize the influence of luminance, and an onset cue was added on one side of the visual field to direct participant's attention to either the left side or the right side. If the results also yield the LSB as in Experiment 1, the possibility of using mean luminance estimation rather than mean size estimation can then be ruled out. In addition, if the results reveal an asymmetric effect between the mean size estimation in the left onset-cue condition

and the right onset-cue condition, the LSB could then be attributed to a leftward attentional bias.

Method

Participants Twenty-six participants (one left-handed and 10 left-eye-dominant) as described on Experiment 1 were recruited.

Apparatus and stimuli The device setting and materials were the same as in Experiment 1, except that the spots were replaced with outline circles, and an additional white frame was added on the left or right visual field to serve as an attentional cue. The cue frame subtended $8.34^\circ \times 12.89^\circ$, and the edge of the frames subtended 0.023° in width. The distance of the center of the frame on each side to the fixation cross was 4.89° . Eye movements were also monitored, and other details were the same as in Experiment 1.

Design A 2 (mean size difference: left-larger, right-larger) \times 2 (cue location: left, right) within-subjects design was adopted. Each combination of mean size difference and cue location combination contained 40 trials, resulting in 160 trials total. The RMSD and AMSD were also calculated as in Experiment 1.

Procedure Participants were given a practice phase with 12 trials (three trials for each condition) before entering the experiment phase in order to ensure that all of them were familiar with the task. The experiment phase was composed of 160 trials that were divided into four blocks. Each block contained 40 trials (10 trials for each condition), and self-paced rest periods were interleaved between each block. Participants pressed the space bar to start each block.

The procedure for each trial was illustrated in Fig. 3. Each trial began with a fixation cross (1,000 ~ 1,200 ms). After the fixation cross, a white frame appeared on one side for 75 ms, followed by a 25-ms blank. Then, a set of outline circles with various sizes appeared for 100 ms, followed by a central outline circle as the test. Participants were instructed to adjust the test circle as accurately as possible until its size was perceived as the same as the M_W by scrolling the mouse wheel and pressing the space bar to confirm their answer. The keyboard and the mouse were aligned with the center of the screen, and participants had to use their right hand to control the mouse while pressing the space bar using their left hand.

Results

Two participants were excluded from further analysis because their mean AMSD were greater than two standard deviations of the mean AMSD of all the participants. All data from the remaining participants were filtered by the

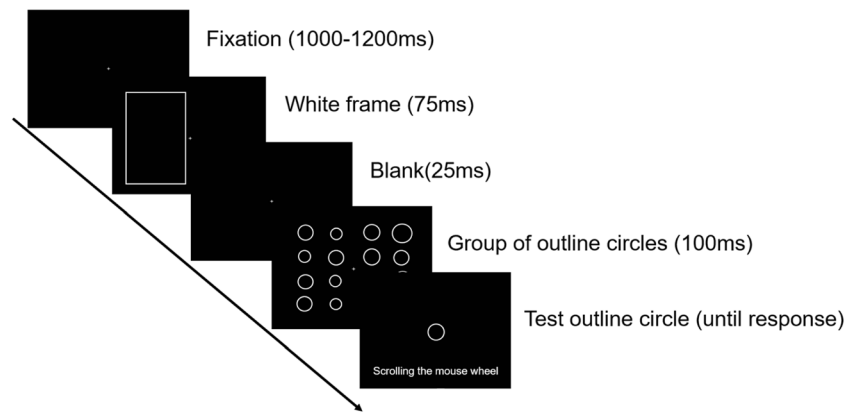


Fig. 3 Procedure of each trial in Experiment 2a. A white frame was presented on the left or the right side as an onset cue for 75 ms, followed by a 25-ms blank. After the blank, a group of spots was

presented for 100 ms and then a test spot appeared. Participants were asked to adjust the test spot to be the same as the M_W

following criteria: all trials with the AMSD higher or lower than two standard deviations of the average AMSD, as well as those where participants could not fixate on the central fixation, were excluded from analyses. Five percent of trials was filtered by these rules.

Figure 4 shows the mean RMSD of the remaining trials for each condition. A 2 (mean size difference: left-larger, right-larger) \times 2 (cue location: left, right) repeated-measures ANOVA was conducted on the RMSD data. The ANOVA revealed a significant main effect of the mean size difference, $F(1, 23) = 10.83, p < .05, \eta_p^2 = .32$; RMSD was greater in the left-larger condition than in the right-larger condition (20% vs. 7%). No other effects were significant ($p > .1$).²

Discussion

The LSB on mean size estimation was also found in this experiment, even when the influence of the luminance was minimized, suggesting that the LSB was due to estimation of mean size rather than mean luminance. Since the results did not show effect of attention manipulation, we suspect that there might have been two effects of attentional capture that happened to cancel out each other. In this experiment, we adopted a white frame to serve as an onset cue before the presentation of the set of outline circles. However, when the outline circles suddenly appeared on the whole screen, it is possible that the circles on the side without the preceding frame served as another onset cue and directed participants' attention to the opposite side of the original (intended) onset cue. If this is what happened, then the two onset cues could have conflicted and canceled out the effect of each other. The

next experiment was designed to exclude this potential problem and see whether attention effect on LSB can be found.

Experiment 2b

In Experiment 2b, the role of attention on the LSB of mean size estimation was investigated again but with a different attentional cueing condition. Two frames were presented initially on both sides, and one was changed to a color frame (the other was changed to a dimmer frame) to direct participant's attention to either the left side or the right side where the color cue was presented. If the LSB on estimating the mean size is due to a leftward attentional bias, then it should diminish when attention is directed to the right side.

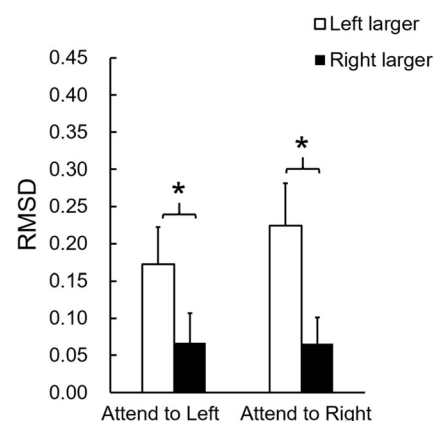


Fig. 4 Results of Experiment 2a. *White bar* indicates larger mean size on the left side and *black bar* refers to larger mean size on the right side. The *black line* above each bar refers to the standard error of the mean for each condition. RMSD = relative mean size difference; * $p < .05$

² The same results were found when we conducted the same analysis on the data of all 26 participants. The ANOVA showed a significant effect of mean size difference, $F(1,25) = 10.63, p < .05, \eta_p^2 = .30$. No other effects were found ($ps > .1$).

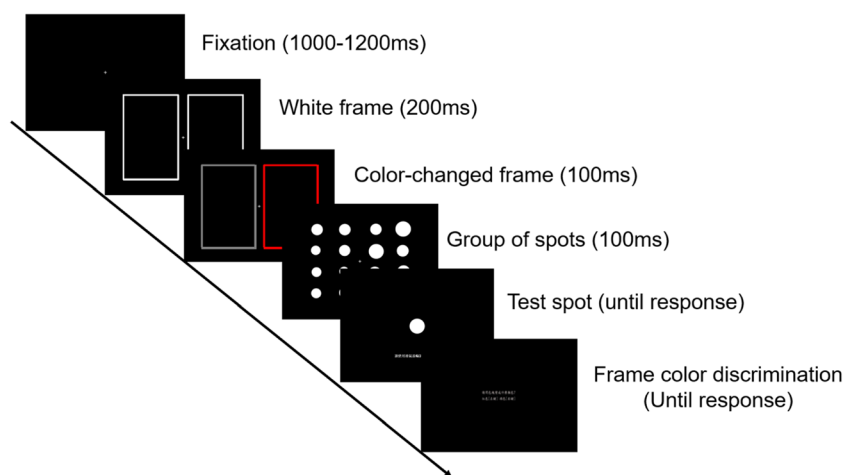


Fig. 5 Procedure of each trial in Experiment 2b. Two white frames were presented on the left side and the right side, respectively. Then the frame on one side turned into red or green (*target frame*), while the other one turned into gray (*distracter frame*). After the color-changed frame, a

group of spots was presented, followed by a test spot. Participants were asked to adjust the test spot to be same as the M_w . After the mean size adjustment task, a second question was presented, and participants had to indicate the color (red or green) of the target frame. (Color figure online)

Method

Participants Twenty-five participants (one left-handed and 10 left-eye-dominant) were recruited in the experiment.

Apparatus and stimuli The setting of the device and the materials were the same as in Experiment 2a, except for three differences. First, we adopted the spots as in Experiment 1. Second, in order to serve as an effective cue, a color cue was used in which the color of one frame was changed from white (RGB: 255, 255, 255) into green (RGB: 0, 255, 0) or red (RGB: 255, 0, 0), and the other frame was changed from white (RGB: 255, 255, 255) to gray (RGB: 128, 128, 128). Third, to ensure that participants paid attention to the color cue, participants were asked to judge the color of the color frame (red or green), which had an edge of 0.23° . Eye movements were also monitored in the same setting and with the same procedure as in Experiment 1.

Design A 2 (mean size difference: left-larger, right-larger) \times 2 (cue location: left, right) within-subjects design was adopted. Each condition of mean size difference and cue location combination contained 40 trials, resulting in 160 trials in total. The dependent variables were the same as in Experiment 1.

Procedure The procedure was the same as in Experiment 2a, except for two differences. First, after the fixation display, two white frames appeared on both sides for 200 ms, followed by a color change. One of the frames would change to either green or red (*target frame*), and the other frame would change to gray (so that there were changes on both sides). The color-

changed frames remained on the screen for 100 ms, and the group of spots appeared immediately after the disappearance of the frames. Second, after the mean size adjustment task, a second question was presented on the screen, and participants were requested to identify the postchange color (red or green) of the target frame. Participants had to press the left arrow key if the target frame was red and the right arrow key if it was green. The key-color correspondence was counterbalanced between participants (see Fig. 5 for an outline of the procedure).

Results

The mean accuracy of the frame color discrimination was 98%, 97%, 98%, and 97% for the four conditions (left-larger + cue on left, right-larger + cue on left, left-larger + cue on right, and right-larger + cue on right), respectively. One of the participants was excluded from further analysis because of high mean AMSD that was greater than two standard deviations of the mean AMSD of all the participants. All data were filtered by the same criteria as used in Experiment 2a and one additional criterion: Trials with incorrect frame color discrimination were excluded from the analysis. By enforcing these criteria, 6.18% of the trials were excluded.

Figure 6 shows the mean RMSD of the remaining trials for each condition. A 2 (mean size difference: left-larger, right-larger) \times 2 (cue location: left, right) repeated-measures ANOVA was conducted on the remaining RMSD data. The ANOVA revealed a significant main effect of the mean size difference, $F(1, 23) = 6.28$, $p < .05$, $\eta_p^2 = .21$; RMSD was greater in the left-larger condition than in the right-larger condition (30% vs. 18%). The ANOVA also demonstrated a

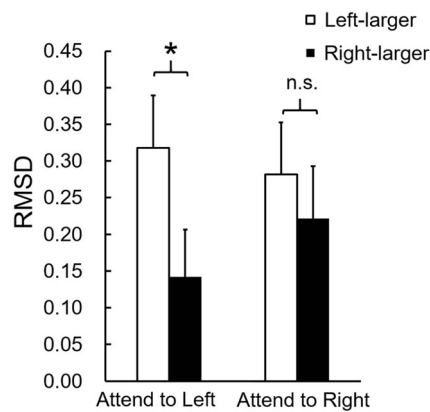


Fig. 6 Results in Experiment 2. *White bar* indicates larger mean size on the left side, and *black bar* refers to larger mean size on the right side. The *black line* above each bar refers to the standard error of the mean for each condition. RMSD = relative mean size difference; * $p < .05$; n.s. = non-significant

significant interaction between mean size difference and cue location, $F(1, 23) = 8.46, p < .01, \eta_p^2 = .27$. Further LSD post hoc tests revealed that, when the cue was on the left side, there was a significant difference between the left-larger and the right-larger condition (32% vs. 14%, $p < .01$). However, no such difference was found when the cue was on the right side (28% vs. 22%, $p = .24$).³

Discussion

The results of this experiment revealed an asymmetrical influence of attentional cue, suggesting that attention plays an important role on the LSB. On the one hand, when participants' attention was cued to the left side, a significant LSB was found, as in Experiment 1. However, when comparing the magnitude of the LSB (the estimated mean size in the left-larger condition minus that in the right-larger condition) found in Experiment 1 and Experiment 2b, directing attention to the left side in Experiment 2b did not increase the magnitude of the bias (11% vs. 17%), $t(46) = .92, p = .37$. On the other hand, the LSB on the mean size estimation disappeared when attention was directed to the right side. More importantly, directing attention to the right side did not shift the estimated mean size toward the mean size of the spots on the right side. In sum,

³ The same analyses were conducted when all participants were included. No difference was found between the results of the analyses with or without excluding the participant. The repeated-measures ANOVA showed a significant interaction between mean size difference and cue location, $F(1, 24) = 4.807, p < .05$. Further LSD post hoc tests revealed that when participant's attention was cued to the left side, the estimated mean size was larger in the left-larger condition than that in the right-larger condition (36% vs. 19%, $p < .05$). The LSB vanished when participants attended to the right side (33% vs. 26%, $p > .1$).

both findings suggest that there is an inherent leftward attentional bias, which accounts for the LSB on mean size estimation.

In line with the discussion of Experiment 2a, in order to exclude the possibility that two attentional capture effects (one elicited by the onset of the white frame, and the other by the onset of spots on the side without prior frame) canceled out each other, here the frames were presented on both sides. Both frames changed their colors, and only one of the frames would become the target with the specific color (red or green). With this procedure, we excluded the onset difference between the left and the right side, and a significant attention effect was found. Taken together the results from Experiments 2a and 2b, an onset cue like in Experiment 2a might not be the best way to investigate the influence of attention on LSB. Later discussions will focus on the results of Experiment 2b.

Experiment 3

In Experiment 2B, we demonstrated that attention plays an important role on the LSB; yet it remains unclear how attention leads to the LSB. Previous studies revealed the existence of the prior entry effect: attended stimuli were perceived earlier than unattended stimuli (Shore, Spence, & Klein, 2001). Shore et al. (2001) used both exogenous and endogenous cues to manipulate participants' attention. Participants were asked to judge the temporal order of two stimuli. They found that the uncued stimuli needed to be presented earlier than the cued stimuli in order for the two stimuli to be perceived as presented simultaneously. Such results implied that attention could speed up the processing of the attended stimuli when compared to the unattended stimuli. Accordingly, we hypothesize that attention induces the LSB by the prior entry effect on the left side. In other words, the prior entry effect may speed up the processing of the spots on the left side, and the processing difference between the two sides may, in turn, induce the LSB.

In Experiment 3, we examined this prior-entry hypothesis by directly manipulating the SOA between the appearance of the spots on the left side and those on the right side. In some cases, all spots were presented simultaneously, while in the other cases, the spots on the left side were presented either earlier or later than those on the right side. If the prior-entry hypothesis is true, the magnitude of the LSB should increase with SOA when the spots on the left side are presented earlier. In contrast, it should first cancel out the LSB and then induce a reverse effect with SOA when the spots on the right side are presented earlier.

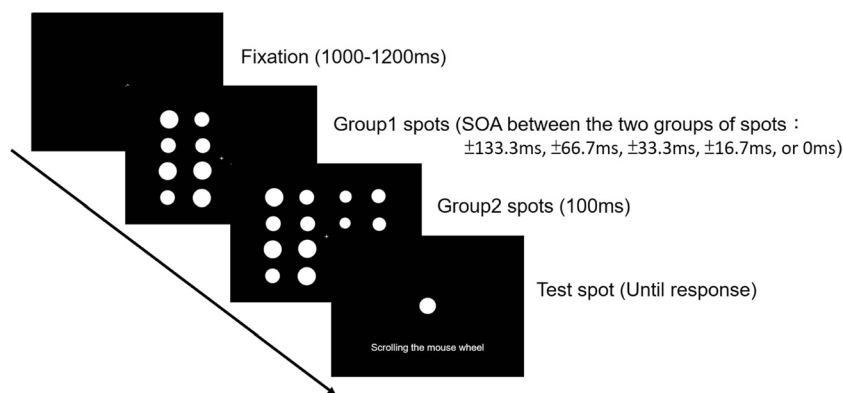


Fig. 7 Procedure of each trial in Experiment 3. One side of the spots was presented earlier than the other side for a specific SOA (in this example, the spots on the left side were presented earlier than those on the right side). There were nine possible SOAs: ± 133.3 ms, ± 66.7 ms, ± 33.3 ms, ± 16.7 ms, 0 ms (positive SOA means the onset of the spots on the right

side was earlier than that on the left side and negative SOA means the reverse). Then both sides of the spots were presented. Following the presentation of the spots, a test spot was shown, and participants were asked to adjust the test spot to be the same as M_W

Method

Participants Twenty-five participants (one left-handed and seven left-eye-dominant) were recruited in this experiment.

Apparatus, stimuli, and design The setting, stimuli, eye-movement monitoring, and design were the same as in Experiment 1, except that in this experiment, each mean size difference condition (left-larger and right-larger) contained nine different SOAs (± 133.3 ms, ± 66.7 ms, ± 33.3 ms, ± 16.7 ms, 0 ms; positive SOA means the onset of the spots on the right side was earlier than that on the left side, and negative SOA means the reverse). Each condition contained 270 trials (30 trials for each SOA), and all of the SOAs were mixed in a block. The dependent variable was the magnitude of LSB, which was defined by the difference between the RMSDs of the two mean size difference conditions (RMSD in the left-larger condition – RMSD in the right-larger condition).

Procedure Eighteen practice trials (one trial per condition) were conducted before the experiment. The experiment contained 540 trials, which were divided into six blocks. Each block contained 90 trials (five trials per condition), and rest periods were inserted between each blocks.

See Fig. 7 for the procedure. Each trial began with a fixation cross (1,000 ~ 1,200 ms), and then the spots. In most of the conditions, the spots on one side (left or right determined by the condition) were presented earlier for 16.7, 33.3, 66.7, or 133.3 ms, followed by the presentation of the spots on the other side. The spots on both sides remained on the screen for 100 ms. In the zero ms SOA condition, the spots on both sides were presented simultaneously for 100 ms. After the presentation of the spots, a central test spot was presented, and participants had to adjust the test spot size until the size

subjectively appeared to be the same as M_W . The device and the response setting were the same as in Experiment 1.

Results and discussion

One of the participants was excluded from further analysis because the participant's mean AMSD was greater than two standard deviations of the mean AMSD of all the participants. And the trials that participants (1) could not fixate on the fixation cross or (2) had AMSDs higher or lower than two standard deviations of the mean AMSD were also excluded. On average, 4.03% trials were excluded.

In order to separate the effect of the SOA on the difference between the two mean size difference conditions, a linear regression analysis was conducted with the magnitude of LSB data.⁴ The analysis showed that the data were well fitted with a linear model ($y = -0.0011x + 0.0163$, $R^2 = .923$), as displayed in Fig. 8. The linear model revealed that when the spots on the left side were presented earlier, the magnitude of the LSB and the SOA correlated positively. In contrast, when the onset of the spots on the right side were presented earlier than that on the left side, the LSB was first reduced and then reversed when the SOA increased.

Furthermore, analogous to the comparison in Experiment 1, a simple *t* test was conducted to compare the RMSD of left-larger and right-larger conditions in the zero-ms SOA condition. Unexpectedly, there was no significant difference in the RMSD between the left-larger and right-larger conditions ($p > .1$). Because any given trial in this experiment was preceded by either a left-side early (negative SOA) trial, a right-side early

⁴ We also analyzed the data without excluding any participant. The variation of LSB magnitude with the SOA were still well fitted with a linear model ($y = -0.0012x + 0.0241$, $R^2 = .91$). There was no difference between the result pattern of analyses based on the data set with or without excluding participants.

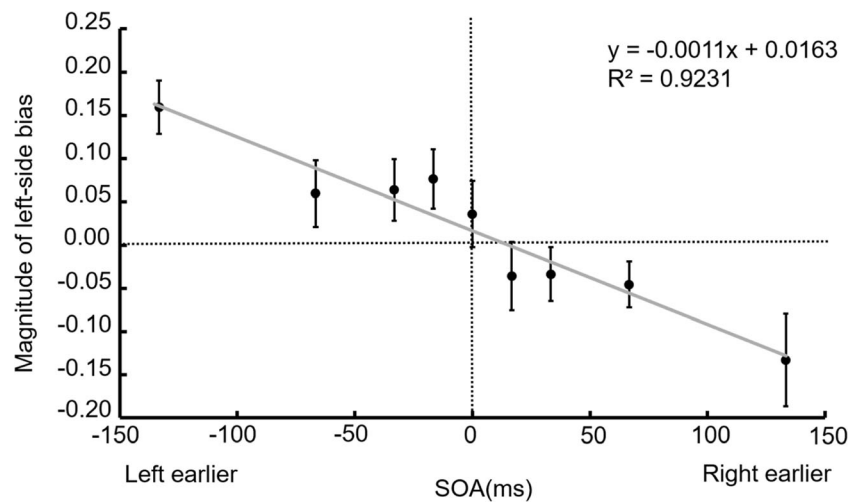


Fig. 8 Linear model (*gray line*) with which the data (*black dot*) of Experiment 3 fitted. *Black lines* around each dot represents one standard error of the mean

(positive SOA) trial, or a zero-ms SOA trial (rarely), when the onset of the right side spots was earlier (i.e., right-side early) in the current trial, participants may predict that the next trial would more likely be a left-side early trial, especially when the right-side early trial had been repeatedly presented for several times. Thus, participants may have paid more attention to the left side in the following trial in that scenario. Conversely, participants may pay more attention to the right-side after a single (or several) left-side early trial (i.e., the onset of the left side spots was earlier). As we have shown in Experiment 2b, the LSB occurred when participants attended to the left side, and was eliminated when participants attended to the right side. Accordingly, both the potential effects of leftward and rightward attention were mixed in the zero-ms SOA condition, which would either reduce or eliminate the LSB. However, we postulate that this mixed effect would be minimized in other SOA conditions because the early onset of stimuli on either the left or the right side in such trial would make the participants reallocate their attention to the corresponding side at the time of stimulus presentation, reducing the mixed effect carried over from preceding trials.

In sum, when estimating the mean size, participants showed the LSB and the magnitude of LSB were modulated by the SOA between the spots on the left and the right side. The linear variation pattern of the LSB with SOA supports the hypothesis that attention induced the LSB on mean size estimation by the prior entry effect on the left side.

General discussion

In the current study, whether the ability to estimate the mean size of a set of items yields the LSB was addressed

by four experiments. In Experiment 1, a significant LSB was found: The estimated mean size was larger when the spots on the left side contained the larger mean size than the smaller, and the confounding of mean luminance difference was excluded (Experiment 2a). This bias disappeared when participants' attention was cued to the right side (Experiment 2b). Furthermore, the LSB was modulated by the SOAs between the onset of the spots on the left side and those on the right side (Experiment 3), where the magnitude of the bias increased with the SOA when the spots on the left side were presented earlier. Conversely, the bias was reduced and then reversed with the SOA when the spots on the right side were displayed earlier. Taken together, the current study demonstrates that estimating the mean size of a set of items with various sizes yields the LSB, and this bias results from an attentional bias toward the left side, which induces the prior entry effect on the left side.

Comparison with other studies

Compared to previous studies, the error of mean size estimation was larger in the current study. Previous studies showed lower than 15% error of the mean size estimation (Ariely, 2001; Chong & Treisman, 2003, 2005b, Experiment 2) whereas the error was around 20% to 40% in our experiments. Such performance difference might result from the different task and materials that we used. In previous studies, participants were either asked to compare the test spot's size with the mean size or to indicate which sets of spots had larger mean size. In both tasks, participants only had to access the difference between two sizes. On the contrary, our experiments asked participants to adjust the test spot to be the same as the mean size of the groups of spots, which required

participants to directly assess the mean size. Perhaps, the difference between tasks may account for the higher error of the mean size estimation in our study. Indeed, the larger estimation error (20%–30%) was also found in Chong and Treisman (2005b, Experiment 3; Chong and Treisman (2005a), where participants were asked to judge which of the test spots matched the mean size. Aside from the difference on the tasks, our materials also differed from previous studies. Specifically, in the present study, the variation of size in the whole set of spots was larger than that in previous studies. Previous studies used two to four different sizes in the whole group (Ariely, 2001; Chong & Treisman, 2003, 2005a, 2005b), while the size of each spot was different in our study. In addition, in order to enlarge the possibility of the LSB, we minimized the overlap between the size distribution of the left and the right side, so most of the spots on one side contained the size larger than the spots on the other side. The above two manipulations of the materials potentially increased the variation of size in the current study and thus may also increase the error of mean size estimation. These differences in tasks and stimuli from previous research may both account for the large estimation error in the current study.

Despite these differences in tasks and materials, the LSB observed in the present study is not an artifact; rather, it is a real perceptual effect. First, our manipulations were the same on both sides, and thus if our manipulations had induced any unwanted effects, the influence of the effects would have been the same on both sides. Second, all of the participants were naïve about the purpose of the study and were instructed that the sizes of the spots were randomly selected. Taken together, there is no reason to infer that the LSB is an artifact that results from the material setting or the instruction that we gave to the participants.

Unequal distribution of attention on mean size estimation

In contrast to the equal distribution hypothesis that attention distributes evenly over each item when estimating the mean size, our results demonstrated an inherent leftward attentional bias that increases the contribution of the information on the left side when estimating the mean size. These results support the view that attention is distributed unequally over the stimuli in the left versus right visual field, since if participants equally distributed their attention to all items over the two visual fields when estimating the mean size, it is unlikely to find the LSB on mean size estimation. More specifically, the LSB on the mean size estimation was consistently found with or without a cue directing one's attention to the left side. In addition, when attention was directed to the right side by a cue, this LSB vanished but was not reversed (Experiment 2b). Although the magnitude difference between the uncued and the cued condition was not significant (11% vs. 17% for Experiment 1 and Experiment 2b, respectively), there was a tendency for

the magnitude of LSB to be larger when participants were cued to attend to the left side compared to when they were not cued at all. The lack of significant difference in the uncued and cued condition can be accounted for by the ceiling effect, as shown in Experiment 3, that the magnitude of LSB was about 15% (Fig. 8) even when the left side was presented 133 ms earlier than the right side. Given that the effect from the inherent leftward attentional bias (11%) had already reached roughly the same level, additional leftward attention manipulation would be less likely to further increase the LSB when estimating the overall mean size. In sum, the asymmetric effect of attentional cue implies an inherent attentional bias to the left side when estimating the mean size.

Mechanism of attention modulation on LSB of perceptual averaging

A possible mechanism may explain this leftward attentional bias on mean size estimation. As mentioned previously, it has been suggested that the right hemisphere is superior in holistic processing compared to the left hemisphere (Christie et al., 2012; Martinez et al., 1997; Yovel et al., 2001). Furthermore, the right hemisphere has been suggested to be more dominant in spatial attention (Gitelman et al., 1999; Mesulam, 1981; Nobre et al., 1997; Weintraub & Mesulam, 1987), as hemispatial neglect occurs more often after right hemisphere damage (Mesulam, 1981, Weintraub & Mesulam, 1987). In addition to studies on neglect patients, research using neuroimaging techniques, such as PET (Nobre et al., 1997) and fMRI (Gitelman et al., 1999) also found a right-hemisphere dominance for spatial attention in healthy adults. That is, when performing the task that requires attentional shift, stronger and more wide-spreading activations in the right hemisphere were found. Perhaps, due to both holistic processing and spatial attention's reliance on the right hemisphere, more attentional resource is directed to the left visual field in mean size estimation.

Attention increases the weight but not the perceived size

The leftward attentional bias increases the contribution of the spots on the left side when estimating mean size, suggesting that not all items equally contribute to the mean property estimation. In the domain of mean property estimation, accumulated studies suggest that elements are not equally weighted during mean property estimation (De Fockert & Marchant, 2008; Haberman & Whitney, 2010; Hubert-Wallander & Boynton, 2015). These studies revealed that, when estimating mean property, our visual system automatically discounted the weight of the outliers (Haberman & Whitney, 2010),

and the weight of the items can also be modulated by attention (De Fockert, & Marchant, 2008), or the temporal order of the items if the items are presented sequentially (i.e., the estimated mean size was more influenced by later objects than the earlier ones; Hubert-Wallander & Boynton, 2015). Our results expanded upon previous findings and demonstrated that when estimating the mean size of a group of simultaneously presented spots, the spots on the left side would be weighted more than those on the right side. Furthermore, we suggest that this asymmetric effect is due to a leftward attentional bias, which induces the prior entry effect that makes the spots on the left side processed faster than those on the right side. This processing difference between the left and the right side in turn modulates the weights of the spots on each side in mean size estimation.

Another study conducted by Charles, Sahraie, and McGeorge (2007) emphasized that the perceived size of a spot was larger in the left visual field than in the right visual field. With this claim, one may consider that the LSB on mean size estimation arises from the perceptual distortion of the size on the left side. Nevertheless, we argued that the distortion of the size perception could not lead to the LSB for the following reason. Because this enlarging effect would occur equally in the left-larger and right-larger condition, such distortion on the estimated mean size should be applied in the same fashion across the two conditions. That is, the enlarging effect would increase the estimated mean size in both conditions without increasing the estimated mean size specific to the left-larger condition. To conclude, we maintained that the LSB on mean size estimation does not result from the distortion of the size perception but from the weighting differences between items on the left versus the right side.

Future direction

In the current study, we only tested the ability to estimate the mean size of a set of spots, so it is still unclear whether forming other types of summary statistic representations, such as mean direction or mean speed, would also yield the LSB. Hubert-Wallander and Boynton (2015) found that not all summary statistic representations were equal. It is therefore likely that the observed LSB in our study would not occur during the estimation of other mean properties. In order to further understand the nature of the summary statistic representations, it is worthwhile for future studies to investigate whether the LSB also exists when estimating the mean value of other features, and if so, whether or not the magnitude of this bias is the same across different features.

Conclusion

Estimating the mean properties of a set of items is an important ability that helps us to deal with the overwhelming amount of inputs in the environment with our limited perceptual capacity. However, the estimated mean property is not always accurate. In the current study, we found that the estimated mean size of a group of spots with various sizes was biased toward the information on the left side. This bias is caused by an automatically shifted attention to the left side, which in turn boost the processing of the items in that area. Our findings suggest that not all items contribute to the mean property equally, and attention modulates the weight of each item on calculating the mean size.

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