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Testing effects in visual short-term memory: The case of an object's size

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Abstract
In many daily activities, we need to form and retain temporary representations of an object's size. Typically, such visual short-term memory (VSTM) representations follow perception and are considered reliable. Here, participants were asked to hold in mind a single simple object for a short duration and to reproduce its size by adjusting the length and width of a test probe. Experiment 1 revealed two powerful findings: First, similar to a recently reported perceptual illusion, participants greatly overestimated the size of open objects – ones with missing boundaries – relative to the same-size fully closed objects. This finding confirms that object boundaries are critical for size perception and memory. Second, and in contrast to perception, even the size of the closed objects was largely overestimated. Both inflation effects were substantial and were replicated and extended in Experiments 2–5. Experiments 6–8 used a different testing procedure to examine whether the overestimation effects are due to inflation of size in VSTM representations or to biases introduced during the reproduction phase. These data showed that while the overestimation of the open objects was repeated, the overestimation of the closed objects was not. Taken together, these findings suggest that similar to perception, only the size representation of open objects is inflated in VSTM. Importantly, they demonstrate the considerable impact of the testing procedure on VSTM tasks and further question the use of reproduction procedures for measuring VSTM.

Keyword s: Visual short-term memory · Testing effects · Object's size · Memory psychophysics · Reproduction · The open-object illusion

Introduction

One of the distinct properties of visual short-term memory (VSTM) is its limited capacity. Consequently, extensive research effort has been directed to characterizing this limitation. While there is an ongoing debate on whether this capacity limit reflects the number of the items that can be held in VSTM or their resolution (e.g., Ma, Husain, & Bays, 2014), most models would agree that holding a single, simple stimulus in memory should not be too challenging. This is because all of the memory resources, or slots, can take part in holding this item in memory (e.g., Zhang & Luck, 2008). Thus, even though VSTM representations are probably not as precise as online, perceptual representations (Brady, Konkle, Gill, Oliva, & Alvarez 2013; Petrusic, Harrison, & Baranski, 2004, but see Magnussen & Dyrnes, 1994), the representation of a single object viewed just a second ago should be fairly accurate. In line with this notion, it was recently reported that much of the fidelity loss of VSTM representations over time is due to inter-item interference, whereas the precision of a single item held in VSTM is hardly lost in the course of a few seconds (Pertzov, Manohar, & Husain, 2016).

From the early days of experimental psychology, one of the popular features to be tested has been a line's length. In fact, probably the earliest experimental test of memory and the earliest use of the "constant stimuli" psychophysical approach was published in 1852 and was about length memory (Laming & Laming, 1992). Accordingly, most of the modern VSTM studies have focused on simple visual features such as colors, orientations, and lengths (Luck & Vogel, 1997). These studies revealed that VSTM for lengths, similar to other simple visual features, is reduced with increased set-size, benefits from precues, and most importantly for the current purposes, does not suffer from any apparent systematic bias (e.g., Palmer, 1988, 1990).

In contrast to line's length, relatively little research has examined VSTM of an object's size. Previous studies that looked

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at this issue often tested the long-term memory of learned magnitudes. That is, these studies typically involved separate learning and testing phases and generally showed that size memory corresponds well to size perception. This, in turn, led to the reasonable conclusion that the memory representations of sizes are noisy forms of the perceptual representations (e.g., Algom, Wolf, & Bergman, 1985; Kemp, 1988; Kerst & Howard, 1978; Petrusic, et al., 2004). However, there are several noticeable differences between this type of *memory psychophysics* studies and standard VSTM experiments. Particularly, the memory psychophysics studies were often interested in comparing the psychophysical functions of perception and (long-term) memory, namely, how the percept/memory changes with increased physical size. By contrast, the goal of the present VSTM study was to evaluate how well people remember the size of a single object they saw just a moment ago.

One of the few studies that tested VSTM for sizes was of Alvarez and Cavanagh (2008, Experiment 4). Using a size change-detection procedure (Luck & Vogel, 1997) it was found that performance was better for isolated rings than for concentric rings. That is, changes in boundary size (isolated ring) were easier to detect than changes in surface texture size (concentric rings). The conclusion from this experiment that boundary information plays an important role in VSTM of sizes is in agreement with a newly reported visual illusion in which simple open-contour objects (ones with missing boundaries) are perceived as bigger than the same-size closed-contour objects (Makovski, 2017). This *open-object illusion* highlights the role of boundaries in size perception (see also Stuart, Bossomaier, & Johnson, 1993) and suggests in turn that this factor might also be central for VSTM of an object's size.

How do object boundaries affect its size memory? If size memory closely follows size perception (e.g., Kerst & Howard, 1978; Petrusic et al., 2004), and size computation relies on the boundaries of the object (Algom et al., 1985; Stuart et al., 1993) then the prediction would be that VSTM of closed objects would be relatively precise, whereas the size of open objects would be overestimated (Makovski, 2017). One could further speculate that the overestimation of the size of the open objects would be amplified in VSTM relative to perception because it is likely that actually seeing both the test and the probe objects in front of you limits the magnitude of the overestimation effect in perception. That is, the ability to make multiple comparisons in matching the size of the two objects in perception could potentially restrict the effect relative to memory, where the memory representation is less likely to be affected by the perceived size of the probe item.

On top of the open versus closed objects effect, a general underestimation bias might also be expected for both types of objects. This prediction was inspired by the boundary-extension effect in which scenes are remembered as having larger boundaries then they actually had, and therefore objects within a scene are remembered as being smaller (Intraub & Dickinson, 2008; Intraub & Richardson, 1989). However, it is not clear whether objects presented in isolation on a blank background are also susceptible to the boundary-extension effect (Gottesman & Intraub, 2002) and hence it is not completely clear whether an underestimation effect should be observed. Notably, given that no other systematic bias has been reported in size perception and memory, there was no reason to predict an overestimation of an object's size in VSTM.

To preview the main findings, Experiment 1 extended the open-object illusion from perception to VSTM, as the size of the open objects was greatly overestimated relative to the size of the closed objects. Unexpectedly and in contrast to the boundary-extension effect, it was further found that the observers also inflated the size of the closed objects. Experiments 2–5 replicated and extended these two inflation effects to other encoding and retention durations, as well as to other open and closed stimuli. Because the overestimation of the closed objects was not expected it was important to test whether it reflected a true inflation of VSTM representations or whether it was a byproduct of the testing method. Thus, Experiments 6–8 tested whether the open and closed overestimation effects were specific to the use of the reproduction procedure. Using a constant stimuli variation of the VSTM task it was found that while the open object overestimation effect was fully repeated, the overestimation of the closed objects completely disappeared.

Experiments 1–5: Reproduction tasks

A previous study found that closed contour shapes are better encoded and recognized than open contour shapes (Garrigan, 2012); however, it is still not known how accurate VSTM of closed and open objects is. Thus, the first set of experiments tested how VSTM of an object's size is affected by the object's boundaries using a reproduction task. Specifically, the stimuli and procedure followed the ones used in the study that tested the role of boundaries in size perception (Makovski, 2017). In that study, it was found that the size perception of the closed objects was fairly accurate, whereas the perceived area of the open objects was inflated by about 15–20% (the open-object illusion). Here, the same stimuli and reproduction procedure were used, only now the tested object did not remain on the screen and participants had to encode its size into VSTM. More specifically, a single, either open or closed, object was presented briefly on the screen and after a short retention interval, the participants were asked to reproduce the size of the object by adjusting the width and length of a simple rectangular probe. If size VSTM follows perception then similar effects should be found here, namely, accurate memory for the size of the closed objects, and overestimation of the size of the open objects.

Method

Participants

Participants in all experiments were undergraduate students from the Open University of Israel who took part in the experiments for a course credit. They all had normal or corrected-to-normal visual acuity. Twenty participants (three males, mean age: 28.0 years) performed Experiment 1.

Equipment and stimuli

Participants were tested individually in a dimly lit room. They sat approximately 67 cm away from a 17-in. CRT monitor (resolution1024 × 768, 85 HZ). The experiments were programmed using Psychtoolbox (Brainard, 1997; Pelli, 1997), implemented in MATLAB (www.mathworks.com). Four memory stimuli were tested: two *Closed* (A & B) and two *Open* (C and D, Fig. 1, top). Each stimulus appeared in one of three sizes: *Small*: 1.94° × 3.89°, *Medium*: 3.24° × 6.48°, and *Large*: 4.54° × 9.07°. The test probe was a simple rectangle (line thickness: 0.03°). The initial size of the probe was randomly selected, with the restriction that its width and length would be within the range of ±1.22° of the memory item.

Procedure and design

Each trial started with a white fixation cross (1.22° × 1.22°) presented against a blue background for 500 ms. Afterwards, the cross disappeared and the memory item was displayed for 200 ms. The memory item could appear 2.7° above or below the center of the screen and 6.75° to the left or to the right. After 900 ms of a blank interval, the test probe appeared at the diagonal position to avoid vertical or horizontal alignment (Fig. 1, bottom).

The task of the participants was to adjust the size of the probe so that it would match the size of the memory item. They used the right and left arrow keys to change the width of the probe and the up and down arrow keys to change its length. Specifically, each keypress increased or decreased the size of the probe by one pixel (~0.027°). Only accuracy was emphasized and participants were instructed to press the spacebar to finalize their response only when they believe the size of the probe matches the size of the memory item.

Each of the four memory stimuli appeared in each of the three sizes eight times (twice in each of the four positions). This resulted in 96 trials that were presented in a randomly mixed order.

Results

The dependent variables were the ratio between the adjusted size of the probe and the actual length, width and area (i.e., the multiplication of the two) of the memory stimulus. Figure 2 plots these values as a function of stimulus type (open, closed) and size (small, medium, large). Repeated-measures ANOVAs with these factors were performed separately for length, width, and area. All of these analyses revealed significant effects of size (all $F(2, 38) > 17.5$, $ps < .001$, $\eta_p^2 > .48$), in that the relative adjusted size was smaller for bigger items (all linear trends were highly robust: $ps < .001$, $\eta_p^2 > .52$). Interestingly, this was the opposite than the trend obtained in perception, where the perceived size increased for bigger items, although those effects were considerably smaller (Makovski, 2017). However, this finding is consistent with the notion that memory for visual areas is compressive in nature (i.e., follows compressive power functions, Algom et al., 1985) and more generally, with the notion that memorial representations are more compressive than their perceptual counterparts (Kerst & Howard, 1978; see also Wiest & Bell, 1985).

Of greater interest, there were strong effects of stimulus type on memory in that the open objects reports were much larger than the reports of the same size closed objects. This was found both in length, $F(1,19)=44.25$, $p<.001$, $\eta_p^2=.70$, width, $F(1, 19)=83.5$, $p<.001$, $\eta_p^2=.82$, and area, $F(1, 19)=60.77$, $p<.001$, $\eta_p^2=.76$. This effect was not modulated by size and none of the interactions between stimulus type and size reached significance (all $ps>.14$). Furthermore, a general overestimation bias was evident as all data points except one (the length of the large closed object) were significantly greater than 1, a value that indicates an accurate estimation (all $ps<.02$). That is, not only that participants were inaccurate in remembering the size of the open objects (they overestimated their area by about 67%), they were relatively poor in remembering the size of the closed objects as well (with an area overestimation of about 27%).

Discussion

Experiment 1 showed that observers have an imprecise memory for sizes as they largely inflate the length, width, and, consequently, the area of a single object held in memory. Moreover, this overestimation bias is even greater for open objects with missing boundaries than for fully closed objects. Both effects were highly consistent with 90% of the participants showing the overestimation of the closed objects, and all participants showing an additional overestimation of the open objects. The latter finding mimics the robust open-object illusion reported in perception. This

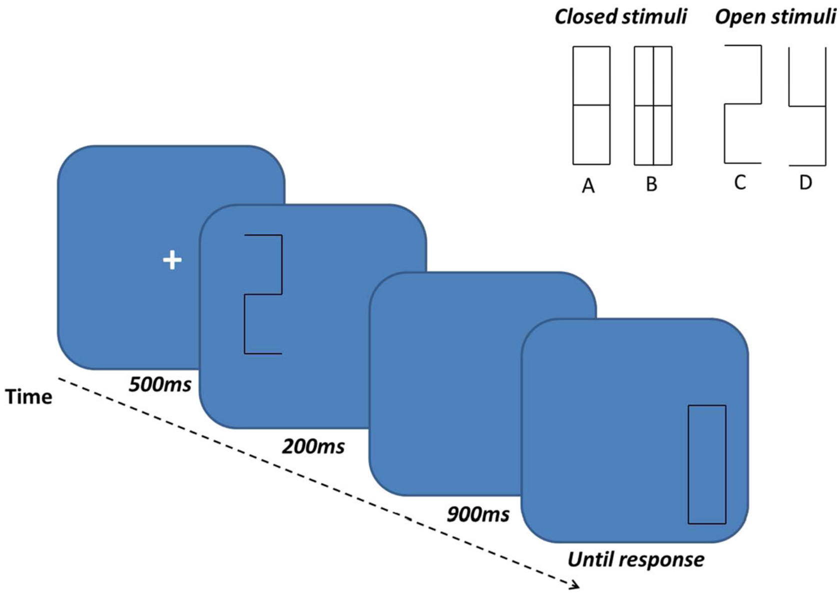

Fig. 1 Top: the closed (**A-B**) and open (**C-D**) stimuli tested in the study. Bottom: a schematic illustration of the trial sequence of Experiment 1

resemblance is also evident in the observation that for these particular open stimuli, the overestimation of the width is larger than the overestimation of the length (although note that this effect was flipped once the objects were rotated, Makovski, 2017, Experiment 4).

Experiment 2: Longer retention duration

Experiment 1 revealed two powerful VSTM effects: First, people are quite inaccurate in remembering the size of a single object and they tend to report it as bigger than it actually was.

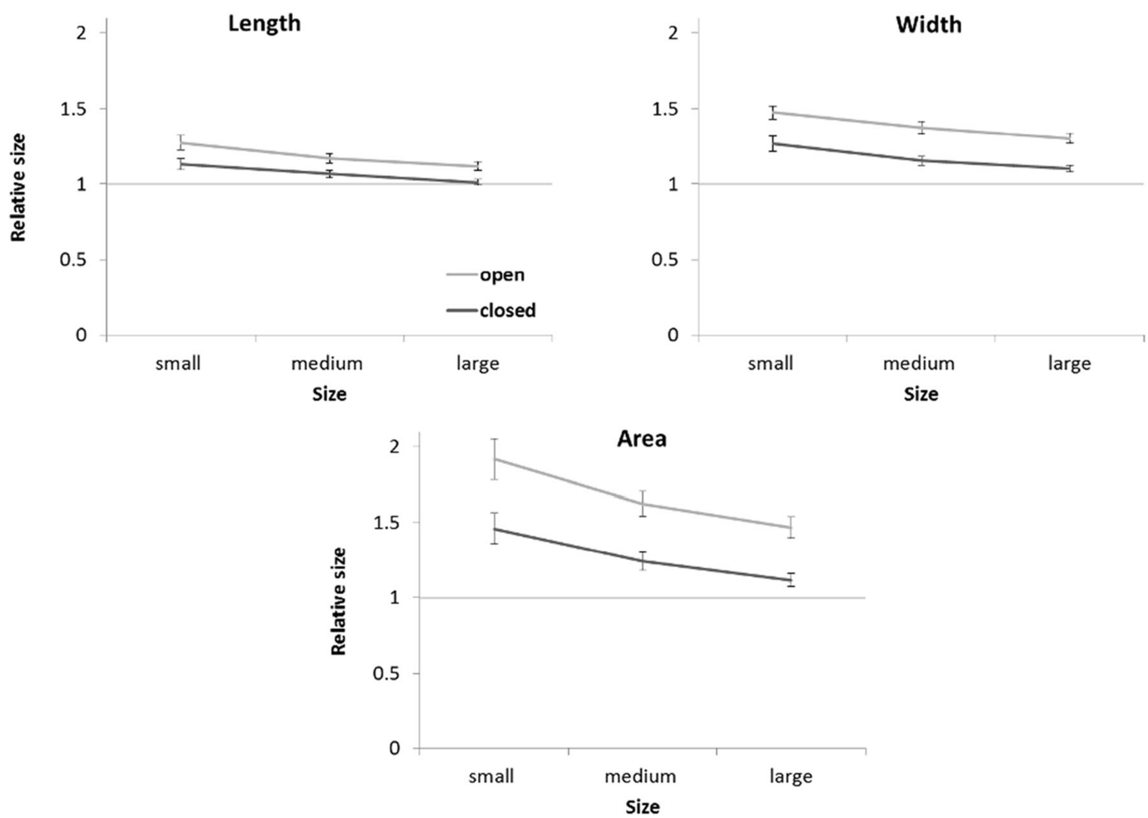

Fig. 2 Results from Experiment 1: Relative length, width and area reports as a function of stimulus type and size. A value of 1 indicates an accurate stimulus-to-probe match, a value greater than 1 indicates that the size of the memory item is overestimated, whereas a value smaller than 1 indicates an underestimation of the size of the memory item. Error bars show ±1 S.E. of the mean

Second, this bias is greater for objects with missing boundaries than for fully closed objects. Together, these two tendencies result in a substantial overestimation of the area of an object they saw just a second ago. Yet, before further discussing the implications of these findings it is necessary to first replicate and extend them. Thus, Experiment 2 repeated Experiment 1's procedure, only now participants were asked to hold the item in memory for a longer duration. This allows us to test whether the inflation effects further grow with time or maybe longer retention duration would actually eliminate the effects.

Method

A new group of 20 participants (four males, mean age: 29.6 years) was tested in Experiment 2, which was identical to Experiment 1 except that the retention interval was increased to 2,300 ms.

Results

Figure 3 depicts the relative length, width, and area as a function of stimulus type and size. Akin to Experiment 1, there were strong effects of stimulus type in that the size reports of the open objects were bigger than of the closed objects for both length, $F(1, 19)=25.65$, $p<.001$, $\eta_p^2=.57$, width, $F(1, 19)=46.79$, $p<.001$, $\eta_p^2=.71$, and area, $F(1, 19)=34.92$, $p<.001$, $\eta_p^2=.65$. The effects of size were also repeated as the relative size decreased for bigger objects (all ps<.001, $\eta_p^2>.6$). However, unlike Experiment 1, there were significant interactions between stimulus type and size and the difference between the open and closed objects decreased with size: length ($p=.004$, $\eta_p^2=.26$), width ($p=.001$, $\eta_p^2=.32$) and area ($p<.001$, $\eta_p^2=.39$).

Similar to Experiment 1, all data points except the length of the large closed object were significantly greater than 1 (ps<.001). Hence, the two previous findings were fully replicated: participants overestimated the area of a closed object held in memory (by ~31%), and this effect was amplified for open objects (overestimation of ~57%). This pattern was found for all participants, indicating that two effects are highly consistent and robust.

Discussion

The results of Experiment 2 indicate that increasing the time that an object is held in VSTM is not sufficient to eliminate or to increase the two inflation effects. If anything, a longer retention interval slightly reduced the difference between the open and closed objects. This was confirmed by direct comparisons between Experiments 1 and 2, which revealed significant interactions between experiment and stimulus type for both length, $F(1, 38)=6.30$, $p=.016$, $\eta_p^2=.14$, width, $F(1, 38)=4.50$, $p=.04$, $\eta_p^2=.11$, and area, $F(1, 38)=4.17$, $p=.048$, $\eta_p^2=.10$. However, there was no overall effect of experiment (all Fs<1), suggesting that the retention duration by itself is not a critical factor in VSTM of size. Notably, only two retention intervals were tested (in separate groups of participants) and therefore additional investigation is needed in order to fully delineate the time course of the inflation effects. Yet, for now, it is safe to conclude that both the general overestimation bias and the open-object effect do not further increase after a longer retention interval.

Experiment 3: Longer encoding duration

The first two experiments showed robust distortions in VSTM of an object size. The next experiment aimed to further generalize these effects and particularly to rule out the possibility that the poor memory for sizes is the result of insufficient time for committing the object into VSTM.

Method

Experiment 3 repeated Experiment 1's procedure with minor modifications. First, to generalize the results, the display parameters followed Makovski (2017), Experiment 2 in that the memory items were slightly bigger and were presented against a red background and closer to the center. That is, the three memory sizes were: *Small*: 2.27° × 4.54°, *Medium*: 3.78° × 7.56°, and *Large*: 5.29° × 10.58°, and the items were positioned 2.16° above or below the center of the screen and 4.32° to the left or to the right. Second, to ensure sufficient time for proper encoding and consolidation the memory item was presented for 1,000 ms instead of 200 ms (the retention duration was set back to 900 ms). Twenty participants (nine males, mean age: 26.5 years) performed this experiment.

Results and discussion

Figure 4 shows the relative length, width, and area as a function of stimulus type and size. The results fully replicated those of Experiment 1: open objects were reported as bigger than closed objects in both length, $F(1, 19)=30.26$, $p<.001$, $\eta_p^2=.61$, width, $F(1, 19)=47.89$, $p<.001$, $\eta_p^2=.72$, and area, $F(1, 19)=39.45$, $p<.001$, $\eta_p^2=.68$. Once again, there were robust effects of size (all ps<.001, $\eta_p^2>.46$), but unlike Experiment 2 and similar to Experiment 1, no significant interaction between stimulus type and size was found (ps>.25).

Parallel to both previous experiments, all data points except the length of the large closed stimulus were significantly greater than 1 (ps<.05). Hence, the two main findings were replicated once again. Participants overestimated the area of a closed object (by ~24%), and even more so the area of an open object (overestimation of ~53%). This effect was not

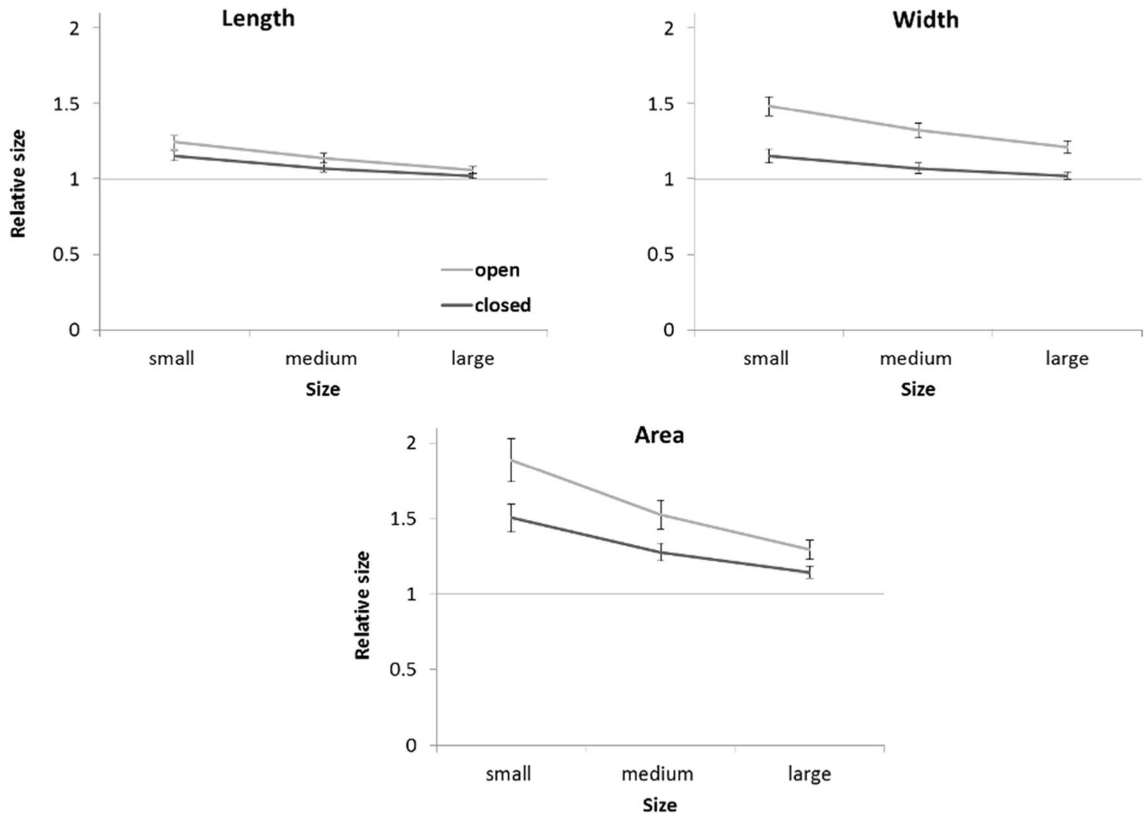

Fig. 3 Results from Experiment 2: Relative length, width and area reports as a function of stimulus type and size. Error bars show ±1 S.E. of the mean

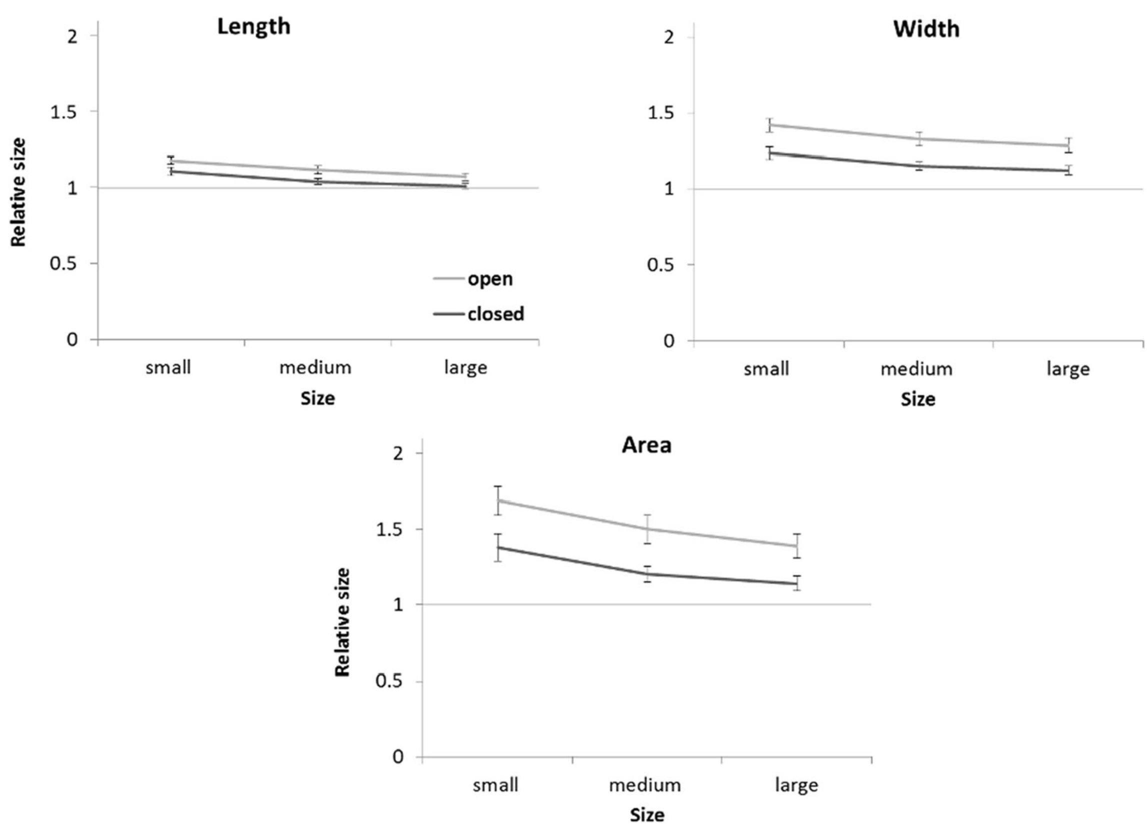

Fig. 4 Results from Experiment 3: Relative length, width, and area reports as a function of stimulus type and size. Error bars show ±1 S.E. of the mean

significantly different to the one found in Experiment 1, $p>.1$. There was also no overall main effect of experiment ($F<1$), refuting the possibility that the open-object effect or the overestimation bias are driven by inadequate encoding.

Experiment 4: Generalization to new stimuli

The goal of Experiment 4 was to extend these inflation effects to other stimuli. To that end, three new open stimuli were tested. In addition, a new closed stimulus was used, and importantly now the closed memory item was identical to the simple, unfilled probe rectangle.

Method

The experiment was identical to Experiment 1, except that three new open objects and one new closed object were used (Fig. 5). Twenty participants (four males, mean age: 27.5 years) performed this experiment.

Results and discussion

Figure 5 shows the relative length, width, and area as a function of stimulus type and size. The results fully replicated those of Experiment 1: the open objects were reported as bigger than the closed object in both length, $F(1, 19)=20.41$, $p<.001$, $\eta_p^2=.52$, width, $F(1, 19)=97.73$, $p<.001$, $\eta_p^2=.83$, and area, $F(1, 19)=36.29$, $p<.001$, $\eta_p^2=.66$. There were also strong effects of size (all ps<.001, $\eta_p^2>.33$) with no significant interaction between stimulus type and size, Fs<1.

All data points were significantly greater than 1 (ps<.05) with the exception of the length of the medium and large closed stimulus and the area of the large closed stimulus. Thus, once again the two main findings were fully replicated. Even when the exact same closed object was used in both the encoding and the test, participants overestimated its area by ~26 % on average. Furthermore, the large inflation of the size of open objects was also replicated with the area of these new stimuli being overestimated by 72% on average.

Experiment 5: Comparing size perception and size VSTM

Does the magnitude of the open-object illusion increase in memory? Indeed, the magnitude of the open-object effect found in Experiment 1 (the relative area of the open objects was ~31% bigger than of the relative area of the closed objects) is numerically greater than the one reported in perception (~15–20%, Makovski, 2017). Thus, to directly compare the magnitude of the overestimation effects in both memory and perception, Experiment 5 tested observers in a version that included both perception and memory tasks.

Method

Each participant in this experiment performed a memory block (as in Experiment 1) and a perceptual block (as in Makovski, 2017) of the size reproduction task. The perceptual version was identical to the memory version, except that the test and the probe items remained on the screen until the participants completed their response. Each block consisted of the four test objects presented in two sizes (2.59° × 5.18° and 3.89° × 7.78°) eight times each. This resulted in 64 trials that were presented in a random order. The order of the two blocks was counterbalanced across participants. Twenty participants (four males, mean age: 27.8 years) completed this experiment.

Results and discussion

Figure 6 shows the relative length, width, and area as a function of stimulus type and task (memory, perception). Repeated-measures ANOVAs with stimulus type and task as factors revealed that the size estimates of the open objects were bigger than the same size closed objects in both length, $F(1, 19)=50.74$, $p<.001$, $\eta_p^2=.73$, width, $F(1, 19)=50.57$, $p<.001$, $\eta_p^2=.73$, and area, $F(1, 19)=44.82$, $p<.001$, $\eta_p^2=.70$. There were also significant effects of task in that the memory task produced larger estimates than the perception task. This was found for width, $F(1, 19)=11.28$, $p<.001$, $\eta_p^2=.37$ and area, $F(1, 19)=6.58$, $p=.02$, $\eta_p^2=.26$, but not for length, $F<1$. Most importantly, there was no interaction between the type of stimulus and task (all ps>.29), suggesting that the magnitude of the open object overestimation is not significantly larger in VSTM than in perception.

Furthermore, all data points were significantly greater than 1 (all ps<.004), implying that the participants overestimated the size of the open objects as well as the closed objects in both perception and in memory. These results somewhat diverge from Makovski (2017), who did not find any overestimation effect for the closed objects in a purely perceptual task. Thus, it is possible that the overestimation of the closed objects in the perception task found here is due to a carryover effect that increased participants reliance on VSTM even in the perception task (e.g., Hollingworth, Richard, & Luck, 2008), especially as only two possible sizes were tested. More important for the current purposes, the overestimation of the area of the closed objects was still highly robust in the VSTM task (25%) and significantly larger than in the perception task (18%, $t(19)=2.22$, $p=.039$).

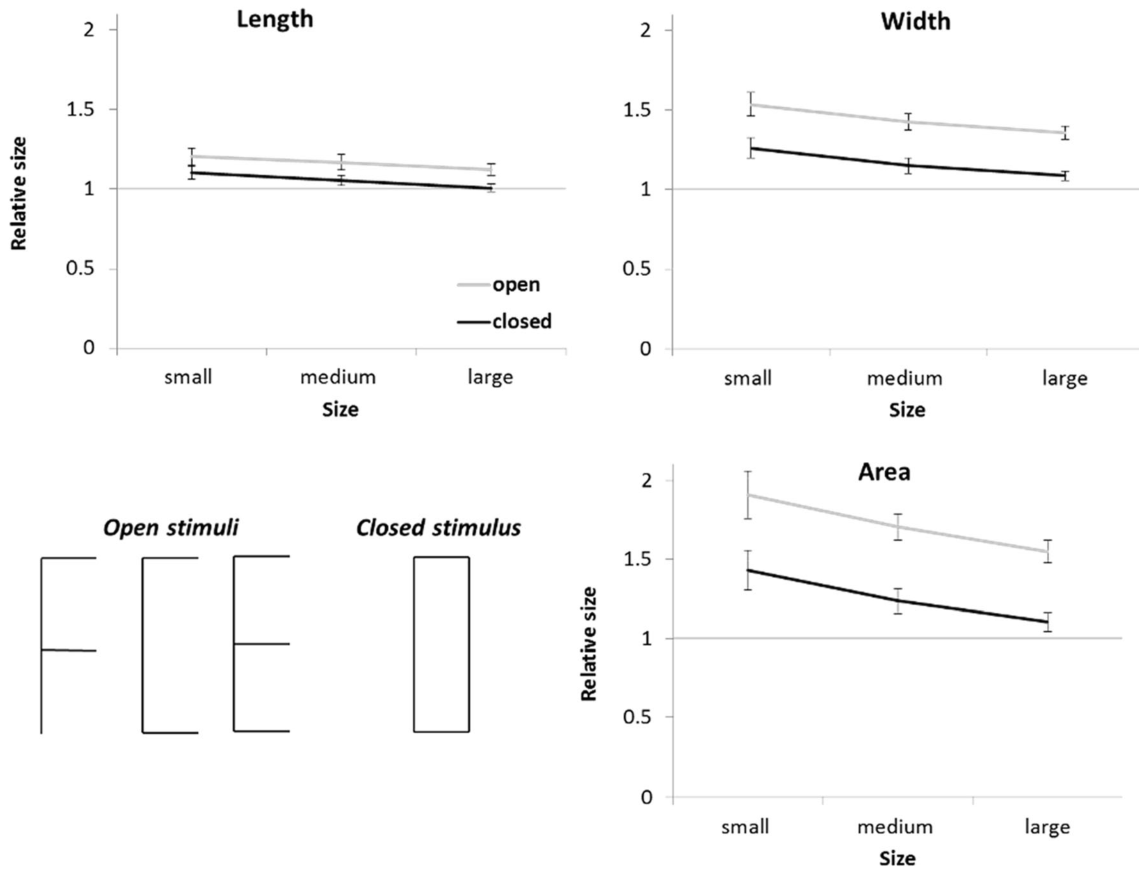

Fig. 5 Experiment 4's stimuli and results: relative length, width and area reports as a function of stimulus type and size. Error bars show ±1 S.E. of the mean

Experiments 6–8: A constant stimuli procedure

The data so far provided strong evidence that people are quite poor in remembering the size of a recently seen object. Specifically, participants greatly overestimated the size of a closed, and to a larger extent, an open object they just viewed a second ago. These VSTM inflation effects were found to be robust and were generalized across different stimulus types, and encoding and retention durations. The inflation effect of the open objects relative to the same-size closed objects follows the open-object illusion found in perception (Makovski, 2017) and, accordingly, the magnitude of both effects seems similar (Experiment 5). By contrast, the size inflation of the closed objects is rather surprising given the implicit assumption that VSTM should not be systematically biased, and because no indication for such a bias was previously reported in size perception. Furthermore, this finding is inconsistent with the boundary-extension effect (Intraub & Dickinson, 2008), which predicted that, if anything, the memory for objects size should be underestimated rather than overestimated.

The next set of experiments was therefore designed to test whether the open-object and the closed-object overestimation effects are due to the use of the reproduction method.[1] That is, it is possible that these overestimation biases do not reflect a "genuine" inflation in the memory representation, rather they are the product of distortions in the memory representation occurring by the retrieval and comparison processes during the test. This possibility is supported by the finding that VSTM estimates are greatly depended on the testing procedure, as sensitivity (d-prime) was much lower when the same stimuli were tested in 2-AFC tasks than in same-different tasks (Makovski, Watson, Koutstaal, & Jiang, 2010). This dependency was specific to VSTM and was not found when more stable representations (i.e., perceptual, long-term memory) were tested, leading the authors to conclude that VSTM is vulnerable to interference from testing. Therefore, in order to test whether the inflation effects found in Experiments 1–5 are due to biases introduced during the reproduction process, Experiments 6–8 tested the size memory of open and closed stimuli using a different testing procedure. If the overestimation effects are driven by inflated VSTM representations then we would expect to find similar overestimation effects when the same stimuli are tested in a different testing procedure. If,

[1] I thank an anonymous reviewer and Dr. C. Philip Beaman for raising this possibility.

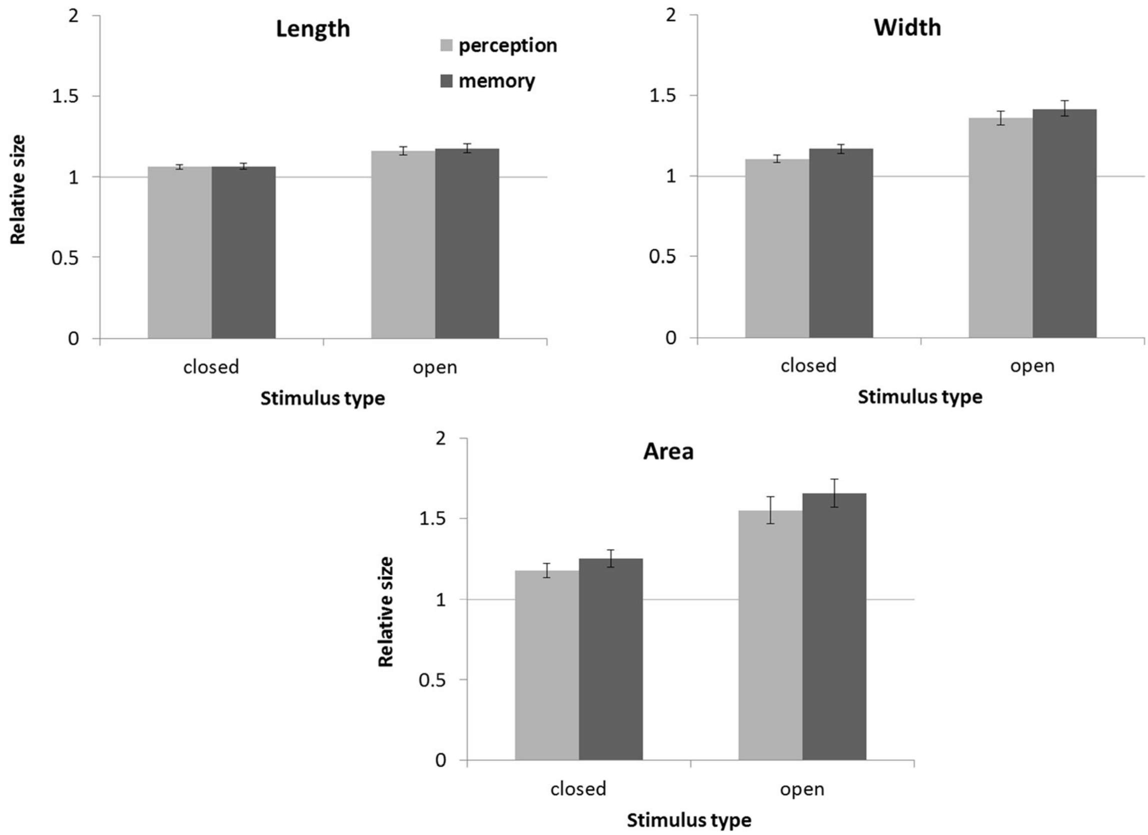

Fig. 6 Results from Experiment 5: Relative length, width and area reports as a function of stimulus type and task. Error bars show ±1 S.E. of the mean

however, the overestimation effects are the result of the reproduction procedure then they should not be observed when size VSTM is estimated differently.

Experiment 6: Which object is bigger?

Method

Experiment 6 repeated the displays of Experiment 1 with the exception that the task of the participants was to determine which one of the two stimuli was bigger. Participants were asked to press the "1" key if they thought that the first item (the memory item) was bigger, and the "2" key if the second item (the probe presented on the screen) was bigger. The memory item appeared in one of the three sizes used in Experiment 1. Importantly, the area size of the probe item could be 70%, 85%, 100%, 115%, or 130% of the area size of the memory item (i.e., 83.7%, 92.2%, 100%, 107.3%, or 114% of the width and length of the memory item). Each of the four objects was tested six times in each of the three memory sizes and the five probe sizes, resulting in 360 trials that were presented in a random order. In all other respects, the method was identical to that of Experiment 1. Twenty participants (two males, mean age: 27.4 years) performed this experiment.

Results

Figure 7 plots the mean proportion of trials in which participants responded that the memory item was bigger than the probe, as a function of stimulus type (open, closed) and the relative area size of the probe (0.7, 0.85, 1, 1.15, 1.3). To increase statistical power, the data from the three memory sizes were collapsed such that each data point from each participant consisted of 36 trials. A repeated-measures ANOVA with stimulus type and relative probe size as factors revealed a strong effect of probe size, $F(4, 76)=64.31$, $p<.001$, $\eta_p^2=.77$. There was also a main effect of stimulus type, $F(1, 19)= 7.64$, $p=.01$, $\eta_p^2=.29$, in that open objects were judged, once again, as bigger than the same size closed objects. This effect was stronger when the size of the probe was closer to the size of the memory item, as indicated by a significant interaction between probe size and stimulus type, $F(4, 76)=4.75$, $p=.002$, $\eta_p^2=.2$.

Importantly, the participants overestimated the size of the open objects in that they reported that the size of the memory item was bigger than the probe in more than 50% of the open object trials (63.3%, $t(19)=3.43$, $p=.003$). However, the participants were quite accurate in the closed object trials in which they reported that the memory item is bigger than the probe in 49.5% of the trials (not significantly different than 50%, $t(19)=-0.14$, $p=.89$). Thus, while a reliable overestimation effect was found for the open objects held in memory (as

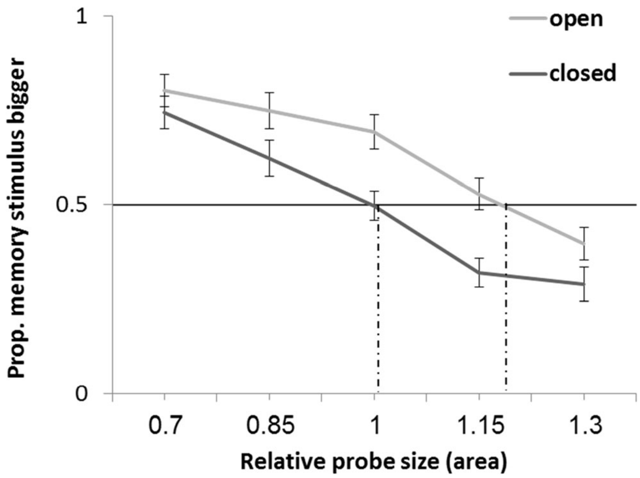

Fig. 7 Results from Experiment 6: Mean proportion of trials in which participants responded that the memory item was bigger than the probe, as a function of stimulus type and probe size. Dotted lines indicate points of subjective equality (PSE) for open and closed objects. Error bars show ±1 S.E. of the mean

also seen by the point of subjective equality (PSE~1.18) in Fig. 7), no bias whatsoever was found for the closed objects (PSE~1.01).

Discussion

The results of Experiment 6 revealed two clear effects: An overestimation of the size of the open objects (as before) and an accurate VSTM representation of the size of the closed objects. The latter finding implies that the testing procedure plays a crucial role in VSTM measurements (see also Makovski et al., 2010). That is, while the reproduction procedure repeatedly showed that participants largely overestimate the size of a closed object held in VSTM, this effect completely disappeared under a different testing condition, even though the same stimuli and displays were used. Thus, taken together these data suggest that the memory representation of the size of the closed objects is by itself accurate and that the overestimation effect observed in the previous experiments is the product of the testing procedure. In contrast, the size of the open objects was overestimated in both testing procedures, supporting the notion that the size representation of an open object is inflated in both perception and VSTM.

Experiments 7–8: Replication and extension

The results of Experiment 6 suggest that only the overestimation of the open objects is driven by a "genuine" inflation of the size of the item held in memory, whereas the overestimation of the closed objects depends on the testing procedure. Before discussing these conclusions further it deemed necessary to replicate and extend Experiment 6's findings. Hence, Experiment 7 repeated the procedure of Experiment 6 using more distinct probe sizes. Specifically, because the overestimation effects were more pronounced for width than for length, it was important to test probes that their relative width (and length) was 0.7, 0.85, 1, 1.15, or 1.3 of the memory item. Experiment 8 further tested whether the results of Experiment 6 depend on the need to compare a memory item with a perceived item, and therefore the probe item was only briefly presented before the participants were making their response.

Method

Experiment 7 was identical to Experiment 6 except for two changes. First, both the length and the width of the probe item were 0.7, 0.85, 1, 1.15, or 1.3 of the memory item (resulting in a relative area of 0.49, 0.7225, 1, 1.3225 and 1.69, respectively). Second, in order to overcome a potential response bias, half of the participants were asked to respond which item was bigger (as before), whereas the other half of the participants were asked to respond which item was smaller. This counterbalance was also employed in Experiment 8 that was otherwise identical to Experiment 6 with the exception that the probe item was displayed for only 200 ms (the same duration as the memory item) before disappearing.

Twenty participants (five males, mean age: 26.5 years) completed Experiment 7 and 26 participants (four males, mean age: 26.8 years) completed Experiment 8.[2]

Results and discussion

Figure 8 depicts the mean proportion of trials in which participants responded that the memory item was bigger than the probe in Experiments 7 and 8, as a function of the stimulus type and the relative size of the probe. As expected, there was a strong effect of probe size in both experiments (Experiment 7: $F(4, 76)=93.92$, $p<.001$, $\eta_p^2=.83$; Experiment 8: $F(4, 100)=35.97$, $p<.001$, $\eta_p^2=.59$). The effect of stimulus type was also repeated in both experiments (Experiment 7: $F(1, 19)= 76.18$, $p<.001$, $\eta_p^2=.8$; Experiment 8: $F(1, 25)= 21.65$, $p<.001$, $\eta_p^2=.46$), confirming, once again, that open objects are judged as bigger than the same size closed objects. The interaction between probe size and stimulus type was significant in Experiment 7, $F(4, 76)=14.87$, $p<.001$, $\eta_p^2=.44$, but not in Experiment 8, $F(4,100)<1$. This is likely because the difference between open and closed objects dissipates in the extreme cases where the size difference between the memory item and the probe is large and consequently the vast majority of the responses are accurate.

As before, participants responded that the size of the memory item was greater than the probe in more than 50% of the open object trials both in Experiment 7 (58.8%, $t(19)=5.29$,

[2] More participants were tested in this experiment because of a technical error.

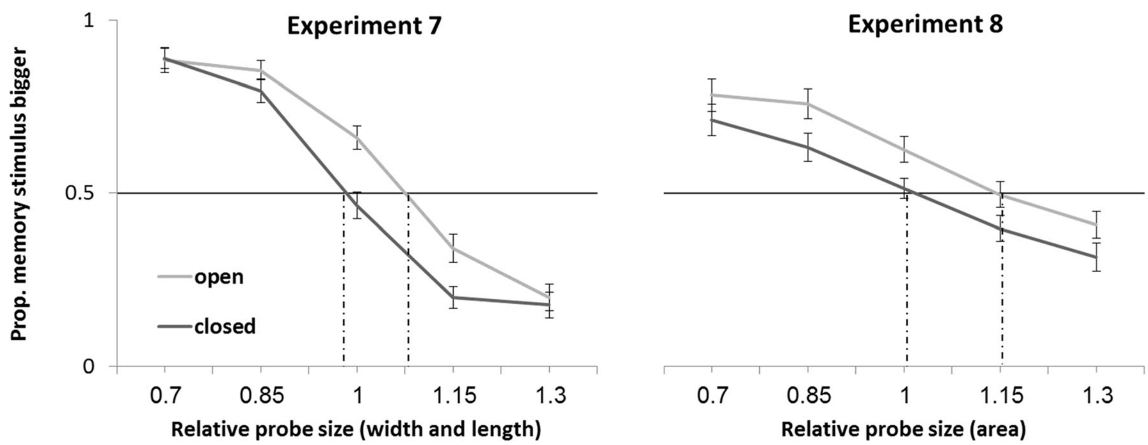

Fig. 8 Results from Experiments 7 and 8: Mean proportion of trials in which participants responded that the memory item was bigger than the probe, as a function of stimulus type and probe size. Dotted lines indicate PSE and error bars show ±1 S.E. of the mean

p<.001) and in Experiment 8 (61.4%, $t(26)=3.62$, $p=.001$). Most importantly, participants were once again quite accurate in the closed object trials responding close to 50% both in Experiment 7 (50.47%, $t(19)=0.28$, $p=.78$) and in Experiment 8 (51.4%, $t(25)=0.5$, $p=.63$). These data, showing overestimation effects for open objects (PSE of ~1.08 and 1.16), with no bias for closed objects (PSE of ~ 0.98 and 1.01) clearly replicate and extend the findings of Experiment 6.

General discussion

In many daily tasks such as packing a suitcase, or filling in a box, we need to hold in mind a visual representation of an object's size for a brief duration (e.g., Triesch, Ballard, Hayhoe, & Sullivan, 2003). The naïve assumption was that this type of temporary memory is a noisy representation of our perception and therefore should not be systematically biased in respect to the perceptual representation (Kemp, 1988; Kerst & Howard, 1978). Nevertheless, the results of Experiments 1-5 suggested that this assumption might not be true and that VSTM of an object's size is systematically biased. Specifically, these data revealed two powerful inflation effects: First, the size of an open object was greatly inflated relative to the same-size fully closed object. This finding is in the same direction and magnitude (Experiment 5) of the overestimation of open objects observed in perception (i.e., the open-object illusion, Makovski, 2017). Second, it was found that unlike size perception, even the size of a single closed object was largely overestimated in VSTM. The combination of these two effects led participants to overestimate the area of a single open object they viewed just a second ago, by more than 50%.

Experiments 6–8 were then conducted in order to test whether these two large overestimation effects are due to the fact that the size of the memory representation is indeed inflated within VSTM, or because the reproduction procedure employed in Experiments 1–5 forced participants to make continuous adjustments, which in turn distorted the memory representation. These experiments found, once again, large overestimations of the size of the open objects, even though VSTM was estimated using a simpler testing procedure (i.e., a variation of the constant stimuli procedure). Hence, it seems safe to conclude that at least the open object overestimation effect is indeed driven by inflated VSTM representations.

In sharp contrast, the overestimation of the size of the closed objects completely disappeared when the testing method was changed, even though the same stimuli and displays were used in both sets of experiments. This discrepancy between the results of Experiments 1–5 and 6–8 indicates that the overestimation of the closed objects does not reflect a genuine inflation of the memory representation. Instead, it seems that the source of the overestimation effect lies somewhere in the testing phase during which participants continuously adjust and compare the size of the probe in front of them with the item held in memory.[3]

Why this continuous adjustment produces a systematic bias in the form of an overestimation of the memory item is currently unclear and additional research is needed in order to clarify this issue. Importantly, however, the considerable difference between the two testing procedures is in line with a recent study that showed the testing method can have a significant effect on VSTM measures (Makovski et al., 2010). This conclusion has an important theoretical implication as it converges with other evidence showing that VSTM representations are vulnerable to test interference (e.g., Makovski, Sussman, & Jiang, 2008; Wang, Theeuwes, & Olivers, 2017). Furthermore, the conclusion that a testing procedure,

[3] Notably, the difference between the two procedures is likely not driven by the longer response latencies in the reproduction procedure, because there was no evidence that by itself the retention duration plays an important role in size VSTM (Experiment 2). There was also no difference in the magnitude of the two overestimation effects found in Experiment 1 when comparing the slow and fast responses of each participant.

and specifically the reproduction method, introduces specific performance biases has significant methodological implications because it challenges the growing use of the reproduction procedure (primarily for estimating VSTM capacity and precision using a mixture-model analysis, e.g., Ma et al., 2014) as a "pure," unbiased estimate of VSTM.

The inflation effect of the open objects is consistent with the open-object illusion reported in perception (Makovski, 2017). That is, observers tend to report the size of an open object as larger than the size of a closed object, regardless of whether the object is in view or not. Furthermore, this open-object inflation effect did not increase when the objects were held in memory for a longer duration (Experiment 2). If anything, there was some evidence that the effect decreased with retention interval, particularly for bigger objects. Experiment 3 further showed that the open-object inflation effect was not modulated by encoding duration and thus, taken together, there is no evidence that unique VSTM processes (e.g., consolidation, retention) enhance the open-object inflation effect. Furthermore, the finding that the magnitude of the open-object inflation effect in memory was not significantly bigger than in perception (Experiment 5) supports the conclusion that the effect in VSTM is driven by the same mechanism and inflated representation as the open-object illusion (Makovski, 2017).

That people inflate the size of an open object in both perception and in memory is also consistent with the finding that closed contour shapes are better encoded and recognized than open contour shapes (Garrigan, 2012). Together, these findings support the notion that the tendency of the visual system to complete the boundaries of open objects results with larger activity in early visual areas (Murray, Kersten, Olshausen, Schrater, & Woods, 2002), which in turn could inflate the perceived, and later remembered, size of an open object. Nonetheless, many questions remain open and it still needs to be seen whether, for example, other stimulus types (e.g., non-rectangular, 3D objects) yield similar findings in both perception and memory.

Conclusions

The study reports two important and novel findings: First, similar to a recently reported perceptual effect, it was found that regardless of the testing procedure; the size of an open object held in VSTM is largely overestimated compared to the same-size closed object. This finding substantiates the notion that object boundaries are critical for size perception and memory. Second, it was found that the size of a single closed object held in memory is largely inflated when tested using a reproduction procedure, but it is accurately judged when a simpler testing procedure is employed. This finding highlights the often overlooked role of testing procedures in VSTM and challenges the use of reproduction procedures in measuring VSTM.

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