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Objects with reduced visibility still contribute to size averaging

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People can rapidly judge the average size of a collection of objects with considerable accuracy. In this study, we tested whether this size-averaging process relies on relatively early object representations or on later object representations that have undergone iterative processing. We asked participants to judge the average size of a set of circles and, in some conditions, presented two additional circles that were either smaller or larger than the average. The additional circles were surrounded by four-dot masks that either lingered longer than the circle array, preventing further processing with object substitution masking (OSM), or disappeared simultaneously with the circle array, allowing the circle representation to reach later visual processing stages. Surprisingly, estimation of average circle size was modulated by both visible circles and circles whose visibility was impaired by OSM. There was also no correlation across participants between the influence of the masked circles and susceptibility to OSM. These findings suggest that relatively early representations of objects can contribute to the size-averaging process despite their reduced visibility.

The world presents the visual system with an enormous amount of information. Many types of visual operations can be overwhelmed, becoming less efficient or less precise if processing is too distributed in scope. Efficiently recovering information often requires focused processing on only a few objects. Yet, even when this scope is distributed to include larger numbers of objects, information about the features and identities of the collection is often still available. Past research suggests that this feeling may be supported by access to statistical summaries of object features, even when precise information about individual objects is not accessible (Ariely, 2001). Much of this research focuses on the feature of object size. In one study, participants viewed a briefly presented display of heterogeneously sized circles and then judged whether a subsequent test circle was present in the first display. The participants were poor at distinguishing circles that were present in the first display from those not present, suggesting that they stored little information about individual objects. But the participants knew the boundaries of the range of possible sizes in the first display and were accurate at rejecting test circles that were outside of this range. A separate experiment showed that even without knowledge of the sizes of individual objects, the participants did have access to the average circle size. Estimates differed from the actual average size of the set by only 4%–12%.

In another series of studies, estimates of average size were actually more accurate when attention was broadly distributed over multiple objects relative to when individual objects were inspected serially (Chong & Treisman, 2005a). Participants saw a brief display of heterogeneously sized circles, and their task was either to estimate the average size of all circles or to report the size of a single object cued after the disappearance of the display. In both cases, the participants performed a secondary task to manipulate whether their region of selection was focused or distributed. In the focused manipulation, the participants either performed a difficult visual search task across the circles or discriminated the orientation of a small rectangle at fixation. In the distributed manipulation, the participants either performed a pop-out visual search among the circles or discriminated the orientation of a rectangle surrounding the objects. The participants were more accurate at the averaging task when the manipulation induced a distributed attentional state. In contrast, the participants were better at reporting the size of a single object when the manipulation induced a focused attention state (Chong & Treisman, 2005a). In another experiment, the participants averaged the size of circles that were presented either simultaneously or sequentially. Averaging accuracy was again higher for simultaneous presentation, suggesting that distributing attention over multiple objects at once leads to higher accuracy in the averaging process. Other experiments have also shown that size-averaging accuracy was not affected by set size (Ariely, 2001; Chong & Treisman, 2003, 2005a, 2005b), suggesting that producing the visual average does not require sequential processing of each object.

Together, these findings have been taken to suggest that the average information arises in a relatively early stage of the visual processing. For example, averages can be extracted with a 50-msec presentation time (Chong &

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Treisman, 2003). Because this time course is short, the representations used for size averaging are extracted at a relatively early stage (Chong & Treisman, 2005b). In addition, the fact that average size information could be retrieved without memory for individual object sizes (Ariely, 2001) and the lack of set-size effects on averaging performance (Ariely, 2001; Chong & Treisman, 2003, 2005a, 2005b) both suggest that averaging occurs in parallel, a hallmark of early processing (Sanocki & Sulman, 2009).

Because the averaging process seems to be quick, effortless, and parallel, researchers have raised the possibility that summary representations are calculated in the early course of perceptual processing (Chong & Treisman, 2003, 2005a, 2005b; Chong, Joo, Emmanouil, & Treisman, 2008; Im & Chong, 2009). However, some aspects of this link are not yet clear. First, many of the findings indicating that the averaging process uses early object representations are only suggestive. Although averages can be computed from a 50-msec presentation (Chong & Treisman, 2003), there could still be a contribution of late visual representations, because previous researchers did not employ masking procedures to gate further processing of the objects. Furthermore, even though averaging performance is more accurate when attention is broadly distributed over multiple objects, it is still possible that the representation used for averaging emerges late in the course of the visual processing. Broad selection might improve size averaging by affecting representations at late processing stages.

Here, we used a different approach to explore whether size averaging relies on either an earlier or a later representation of a collection of objects. Instead of manipulating set size or presentation time, we gated the stage of processing using masking. In many traditional masking procedures, such as lateral or pattern masking, a mask stimulus is presented temporally or spatially adjacent to the targeted object. These types of masking could impair performance because of integration of the mask and target stimulus (Di Lollo, 1980; Kahneman, 1968; Turvey, 1973), the interruption of ongoing perceptual processing (Kolers, 1968; Michaels & Turvey, 1979; Spencer & Shuntich, 1970), or competitive neural interactions between target and mask representation (Breitmeyer & Ganz, 1976; Keysers & Perrett, 2002; Weisstein, Ozog, & Szoc, 1975). However, we did not use lateral or pattern masking, because they may alter early neural representations of the object. Instead, we used a technique that appears to alter only later visual representations: object substitution masking (OSM). In a typical OSM procedure, a mask consisting of four dots surrounds an enclosed object but does not touch it. If the enclosed object and mask are briefly presented but disappear at the same time, the initial object representation is preserved, and the object is consciously perceived. But if the mask remains longer than the object, the object is often invisible. Many accounts of OSM suggest that the mask substitutes for an initial representation of the object within an iterative sequence of feedback from higher visual areas (Di Lollo, Enns, & Rensink, 2000, 2002; Enns, 2004, 2008; Enns & Di Lollo, 1997). As a result, people can access only the late representation, a blank surrounded by the four-dot mask. One account of OSM suggests two separate stages of the perceptual consolidation: object formation and object substitution (Enns, 2004). For the first 100 msec after the target presentation, the visual system forms an initial object representation. Once the initial object representation is formed, the visual system revisits and updates the object until the quality of the representation exceeds the threshold of conscious perception. Any information updated during this iterative reentering processing contributes to later object representation. This late object representation then substitutes for the early representation.

Neurophysiological evidence suggests that OSM can be used to gate the processing stage of an object representation. One study showed that OSM diminished the amplitude of N400, a relatively late ERP component related to semantic processing (Reiss & Hoffman, 2006). OSM was also shown to eliminate N170, another late ERP component related to object recognition (Reiss & Hoffman, 2007). Another study also showed that OSM could selectively interfere with the late stage of object consolidation using fMRI. In this study, the neural adaptation for the masked object, which is a signature of the repetition of the same neural representation, was present in early visual areas, such as V1, but not in higher level visual areas, such as lateral occipital cortex (LOC; Carlson, Rauschenberger, & Verstraten, 2007). This study suggests that OSM does not eliminate traces of early object representation altogether, but it does impair later processing, such as object recognition. In addition, a target with reduced visibility due to OSM still evoked a shift of attention that usually accompanies the target identification, as was measured by the ERP N2pc component (Woodman & Luck, 2003). A recent behavioral study also suggests that OSM does not completely block some types of early shape processing, even when OSM impairs conscious awareness of those shapes (Chen & Treisman, 2009). In this study, participants were briefly shown a center set of arrows, flanked by four additional sets of arrows with either compatible or incompatible orientations. These flanking arrows disappeared either with the center arrow, leaving the center arrow visible, or slightly after the center arrow, creating OSM and impairing conscious perception of the center arrow. When the participants reported the direction of the flanking arrows, the compatibility of the masked center arrow had a systematic influence on the speed of the mask discrimination task, even if the participants reported no percept of the center arrow. These results suggest that some types of early shape processing can still occur in the presence of OSM and can affect other visual processes. Together, past studies on OSM strongly suggest that OSM can gate late perceptual processing while preserving relatively early object representations.

In the present study, we explored the representation underlying the size averaging process by using OSM to manipulate the type of representations available. We displayed two masked circles[1] and tested whether the size of these circles could still contribute to the averaging process. We also included a condition in which the masks would disappear simultaneously with the circle, leaving the circles visible, and leaving later representations intact. Finally, we also included trials with two masks, but without circles presented inside, as a baseline to measure any effects of the mask itself on the size-averaging process. If the two extra masked objects participate in the averaging process, the average information must be at least partially based on initial object representations. Otherwise, if the masked objects do not affect the average estimation, the averaging may instead rely on later object representations that have benefited from iterative processing.

EXPERIMENTS 1A AND 1B

In Experiment 1B, we asked participants to estimate the average size of a set of circles. Two extra circles were present, surrounded by dots that disappeared after the circles (masking) or surrounded by dots that disappeared simultaneously with the circles (no masking). In the third condition, the dots were presented alone with no circles. But first, in a separate control experiment (Experiment 1A), we conducted a conservative test of how strongly our OSM manipulation blocks conscious access to the size of a cued circle.

Experiment 1A: Control Experiment (Visibility Test)

Method

Participants. Eight undergraduates at Northwestern University participated for course credit. All of the participants reported normal or corrected-to-normal vision.

Stimuli and Apparatus. Eight circles were presented with center points at one of the equally spaced locations of an imaginary circular array 10º in diameter. The task was to report whether a target surrounded by a four-dot mask was larger or smaller than the distractor circles. In a control experiment, we used three size sets, each consisting of three circles with different diameters: (1) 0.6º, 1.2º, 1.5º; (2) 0.9º, 1.5º, 2.1º; and (3) 2.1º, 2.4º, 2.7º. Each size set was displayed an equal number of times during the experiment. The smallest circle of each size set served as a target in half of the trials; the largest circle served as target in the other half of the trials. The medium-sized circles from the three size sets were used as distractors. The target was presented at one of the eight locations with equal probability. The four dots were located at the corners of an imaginary square, 2.86º in diameter, and the size of each dot was 0.4º. All foreground objects, including circles and fixation, were displayed in dark gray (approximately 7.7 cd/m^2) on a gray background (approximately 29.3 cd/m^2). The four-dot mask was displayed in red (approximately 19.2 cd/m^2) in order to keep the four-dot mask distinguishable from the circles. Although this manipulation should actually weaken OSM strength (Moore & Lleras, 2005), using a dissimilar color for the four-dot mask should minimize the participants' use of the size of the mask itself as input to the average circle size judgment. The experiment was run using MATLAB with PsychToolbox (Brainard, 1997; Pelli, 1997) on an Intel Macintosh running OX 10.5. All stimuli were displayed on a 17-in. ViewSonic E70fB CRT monitor with 1,024 × 786 pixel resolution and an 85-Hz refresh rate. The viewing distance was approximately 57 cm.

Procedure. Figure 1A shows a schematic procedure of the control experiment. Once a trial was initiated, a fixation cross was displayed for 1,500–2,500 msec. A set of eight circles then appeared for 30 msec. The task was to report the relative size of the target circle, which was indicated by a red four-dot mask. Across the experiment, either the dots disappeared simultaneously with the circles (simultaneous condition) or they disappeared with a 320-msec delay (delayed condition). In the simultaneous condition, a blank screen followed the circle display for 320 msec. In both conditions, a blank display was presented until the participants' response. In half of the trials, the large circle was chosen as a target from one of the three size sets (large condition). In the other half of the trials, the small circle was chosen as a target (small condition). The participants were instructed to press the "/" key if the object enclosed by the mask was large and the "." key if it was small. They were instructed to press the "z" key when they failed to perceive the target. For each size set, there were 40 trials for each combination of target circle type (large vs. small) and mask type (simultaneous vs. delayed), for a total of 160 trials. The experiment included 6 practice trials and 480 experimental trials and lasted about 40 min.

Results and Discussion

Figure 2 shows the distribution of the three response types across conditions. As was expected, the percentage of correct responses was lower in the delayed condition than in the simultaneous condition across all three size sets. In contrast, the percentage of no-percept responses was higher in the delayed condition than in the simultaneous condition in general. After the wrong responses and no-percept responses were collapsed together, the average percentage of correct percepts was examined with a 2 × 2 × 3 repeated measures ANOVA using three factors: circle type, mask type, and circle size set. Although there was a significant main effect of the circle size set [$F(2,14) = 9.58$, $p = .002$, $\eta^2 = .58$] [Size Set 1 (0.6º, 1.2º, 1.5º), $M = 70.00\%$, $SE = 4.78\%$; Set Size 2 (0.9º, 1.5º, 2.1º), $M = 64.61\%$, $SE = 4.44\%$; Set Size 3 (2.1º, 2.4º, 2.7º), $M = 71.48\%$, $SE = 4.38\%$], the size-set factor did not interact with the other two main factors, nor was there a significant interaction among the three factors [size set × circle type, $F(2,14) = 1.89$, $p = .188$, $\eta^2 = .21$; size set × mask type, $F(2,14) = 1.26$, $p = .315$, $\eta^2 = .15$; size set × circle type × mask type, $F(2,14) = 1.24$, $p = .319$, $\eta^2 = .15$]. In addition, there was no significant main effect of the circle type [$F(1,7) = 1.58$, $p = .249$, $\eta^2 = .18$]. A significant main effect of mask type, however, was found, as was expected [$F(1,7) = 10.15$, $p = .015$, $\eta^2 = .59$], suggesting that our OSM procedure could decrease the conscious perception of the individual circle size (simultaneous, $M = 81.09\%$, $SE = 2.50\%$; delayed, $M = 56.30\%$, $SE = 7.96\%$). No interaction between circle and mask type was found [$F(1,7) = 2.40$, $p = .166$, $\eta^2 = .26$], indicating that OSM was present to a similar degree across small and large circles.

Experiment 1B: Average Size Judgment

Method

Participants. Fifteen undergraduates at Northwestern University participated for course credit or monetary compensation. All of the participants reported normal or corrected-to-normal vision.

Stimuli and Apparatus. The stimuli in Experiment 1B were identical to those in the control experiment (Experiment 1A) except for the following: The diameter of the six circles was randomly chosen from 0.3º increments within a range of 0.9º–2.4º. In the absent condition, no extra circle was displayed. In the present condition, the two extra circle sizes were presented and could be 0.9º or 2.4º in the small or large condition, respectively. The locations of the two extra circles were counterbalanced across trials.

Procedure. Once a trial was initiated, a fixation cross was displayed for 1,500–2,500 msec. Then, a set of six circles was presented for 30 msec, with or without two extra circles surrounded by dots. The task was to guess the average size of all of the circles.

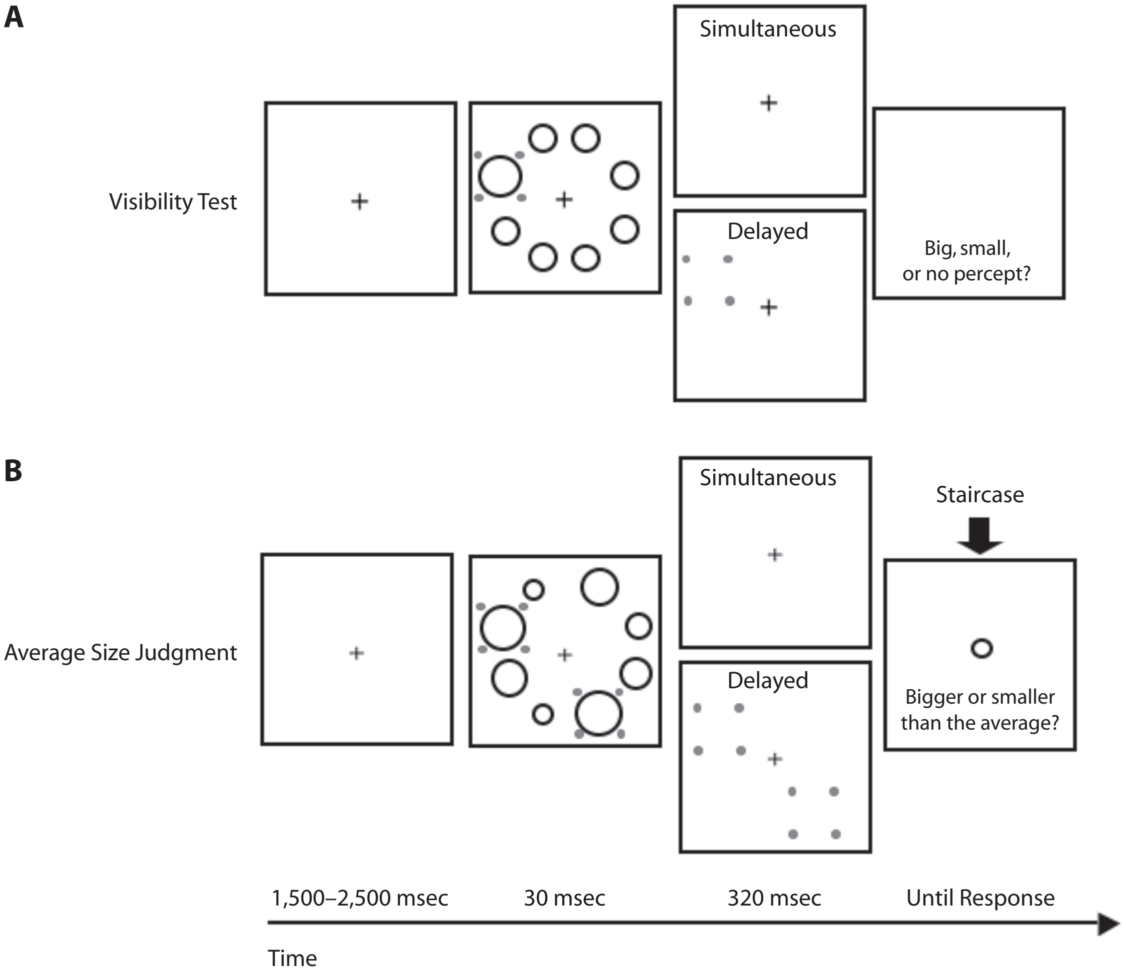

Figure 1. A schematic of the procedure for Experiment 1. (A) The procedure for the visibility test. (B) The procedure for the average size judgment task.

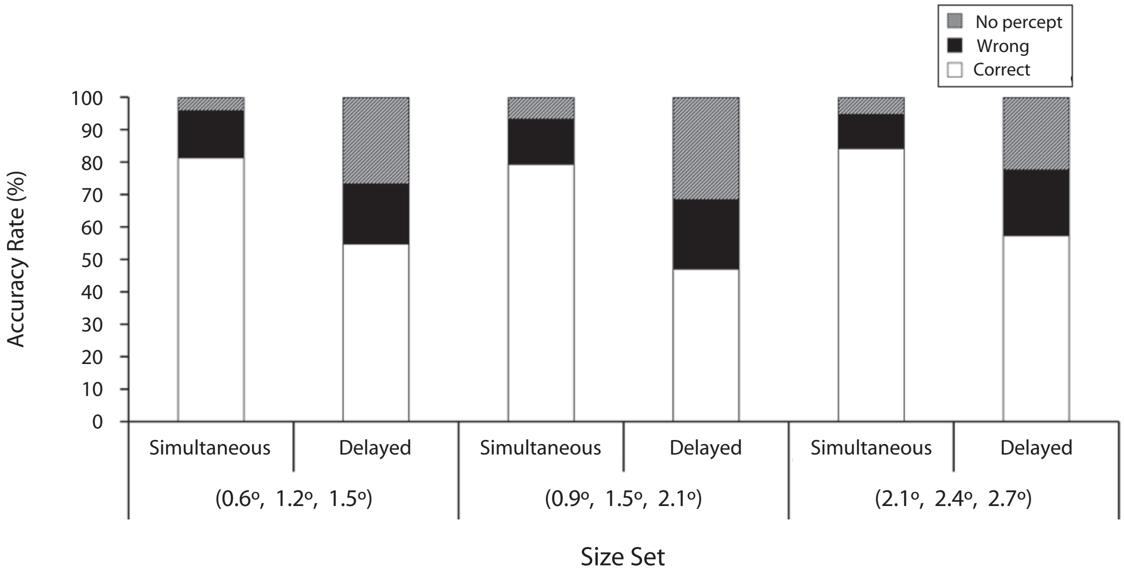

Figure 2. The percentages of the three response types in the simultaneous and delayed mask conditions across three different size sets. Responses of the large and small circle conditions were collapsed. The percentages of the correct, wrong, and no-percept responses are stacked together. White bars stand for the correct responses; black bars, wrong responses; and striped bars, no-percept responses.

Masks disappeared either simultaneously with the circles (simultaneous condition) or with a 320-msec delay (delayed condition). The control experiment showed that delaying the disappearance of the mask impaired conscious perception of the size of the initial circle. In both the simultaneous and delayed conditions, the extra circles either were the largest (large condition) or the smallest (small condition) size from the circle size range of 0.9º–2.4º or were not present (mask-only condition).

The participants were instructed to compare a reference circle shown on the screen with their estimate of the mean size of the previous set of circles (see Figure 1B). The size of the reference circle was adjusted using a staircase procedure. Because there were multiple sets of object sizes, the size of the reference circle was represented across trials as a percentage difference between the average circle size (not including the extra circles, when present) and the reference circle size. Whenever the participants responded that the reference circle was larger than their estimated average size, the size of the next reference circle was decreased by 3%, and a *smaller* response caused the next reference circle to be increased by 3%. The initial value of the staircase could be either 20% smaller or 20% larger than the average size of the six circles and was counterbalanced across the mask-only, large, and small conditions (AAB, ABA, ABB, BAA, BAB, and BBA). To measure the perceived average size of the six mask × circle conditions, we calculated the point of subjective equality (PSE) for each trial as the difference between the size of the reference circle and the average size of the six circles divided by the average size of the six circles. We then averaged this value across the last 12 staircase reversal trials out of all reversals (M = 38.78, SD = 4.56; Min = 26, Max = 51) for each condition for each participant. The participants were not given feedback about their responses, in order to minimize the potential influence of strategic adjustments of size estimates (Bauer, 2009). The experiment included 15 blocks of 48 trials each, resulting in a total of 720 trials. These trials were equally assigned across the mask (simultaneous vs. delayed) × circle (control vs. large vs. small) conditions, resulting in 120 trials per condition. The participants were given self-timed breaks after finishing a set of 72 trials. The main experiment, including 12 practice trials, lasted approximately 40 min.

Results and Discussion

Figure 3A shows the average PSE across participants. The participants tended to overestimate the average size, even in the control simultaneous condition, where neither extra circles nor delayed four-dot masks were presented [$t(14) = 2.28, p = .039$]. This general overestimation bias is consistent with findings in previous studies (Bauer, 2009; Chong & Treisman, 2003). To test whether circles masked by OSM still contributed to the averaging process, the PSE of average size in all six conditions was entered in a repeated measures 2 × 3 ANOVA with the factors mask type (simultaneous vs. delayed) and circle type (mask only vs. large vs. small). Greenhouse–Geisser correction was employed to adjust the degrees of freedom because of sphericity violations. We found a significant circle type effect [$F(1.18, 16.56) = 13.23, p < .0001, \eta^2 = .49$], indicating that the size of the two extra circles influenced the size average judgment. This main effect was driven by significant differences between the members of all the three possible pairs: between the large (M = 27.10%, SE = 6.00%) and the mask-only (M = 16.33%, SE = 6.38%) conditions [$t(14) = 3.25\ p = .006$], between the small (M = 13.17%, SE = 6.08%) and the mask-only conditions [$t(14) = 2.70, p = .017$], and between the large and the small conditions [$t(14) = 4.05, p = .001$]. When the two extra circles were of the largest of the possible circle sizes, the estimated average circle size was larger than that in the mask-only condition. In contrast, the average circle size was estimated as smaller than that in the mask-only condition when the two extra circles were of the smallest possible sizes. There was also a significant mask type effect [$F(1,14) = 12.03, p = .004, \eta^2 = .46$], where the participants tended to overestimate average size in the delayed condition (M = 20.73%, SE = 6.12%) relative to that in the simultaneous condition (M = 17.00%, SE = 5.80%). There was no significant interaction between circle and mask type [$F(1.26, 17.57) = 1.64, p = .22, \eta^2 = .105$]. Regardless of whether the masks disappeared simultaneously with the circle display or stayed longer than the circle display, the PSE of average size was affected by the size of masked circles. This result suggests that masked circles contributed to the perception of average circle size as much as unmasked circles.

An unexpected and interesting finding was that size overestimation was greater in the delayed disappearance condition than in the simultaneous disappearance condition. The participants overestimated the average size of the circles even more when the four-dot mask lingered longer than the object relative to when it disappeared simultaneously with the object. One possible interpretation is that the area subtended by the four-dot mask, which was always larger than the object size, was included in a process of size averaging. In other words, the participants might have been unable to ignore the size of the imaginary square formed by connecting four dots and might have taken the size of this area into the average calculation.

To cancel out the effects of the size of the area subtended by the four-dot masks on the size-average judgment, we subtracted the PSE observed in the control conditions from that in the large and small conditions. In the resulting data (Figure 3B), four different circle type × mask type conditions were produced: simultaneous large–simultaneous mask only, simultaneous small–simultaneous mask only, delayed large–delayed mask only, and delayed small–delayed mask only. If the perceived average size were affected by circle size with low visibility, we would find a significant effect of circle size in both the simultaneous and the delayed conditions. If the perceived average size were solely affected by the size of the area subtended by the four-dot masks, we would not find any modulation by the circle size in the delayed condition. We entered the difference in the PSE between the mask-only condition and the large and small conditions into a 2 × 2 repeated measures ANOVA using the two factors circle size (large vs. small) and mask (simultaneous vs. delayed). The results showed a significant main effect of circle size [$F(1,14) = 16.42, p = .001, \eta^2 = .54$], indicating that the participants estimated the average size as larger in the large condition (M = 10.77%, SE = 3.32%) than in the small condition (M = −3.17%, SE = 1.17%). However, we could find neither a significant main effect of mask [$F(1,14) = 1.86, p = .194, \eta^2 = .12$] nor an interaction of circle size and mask [$F(1,14) = 1.58, p = .230, \eta^2 = .10$]. These results suggest that objects whose visibility was impaired because of OSM affected the average size judgment as much as clearly visible objects did.

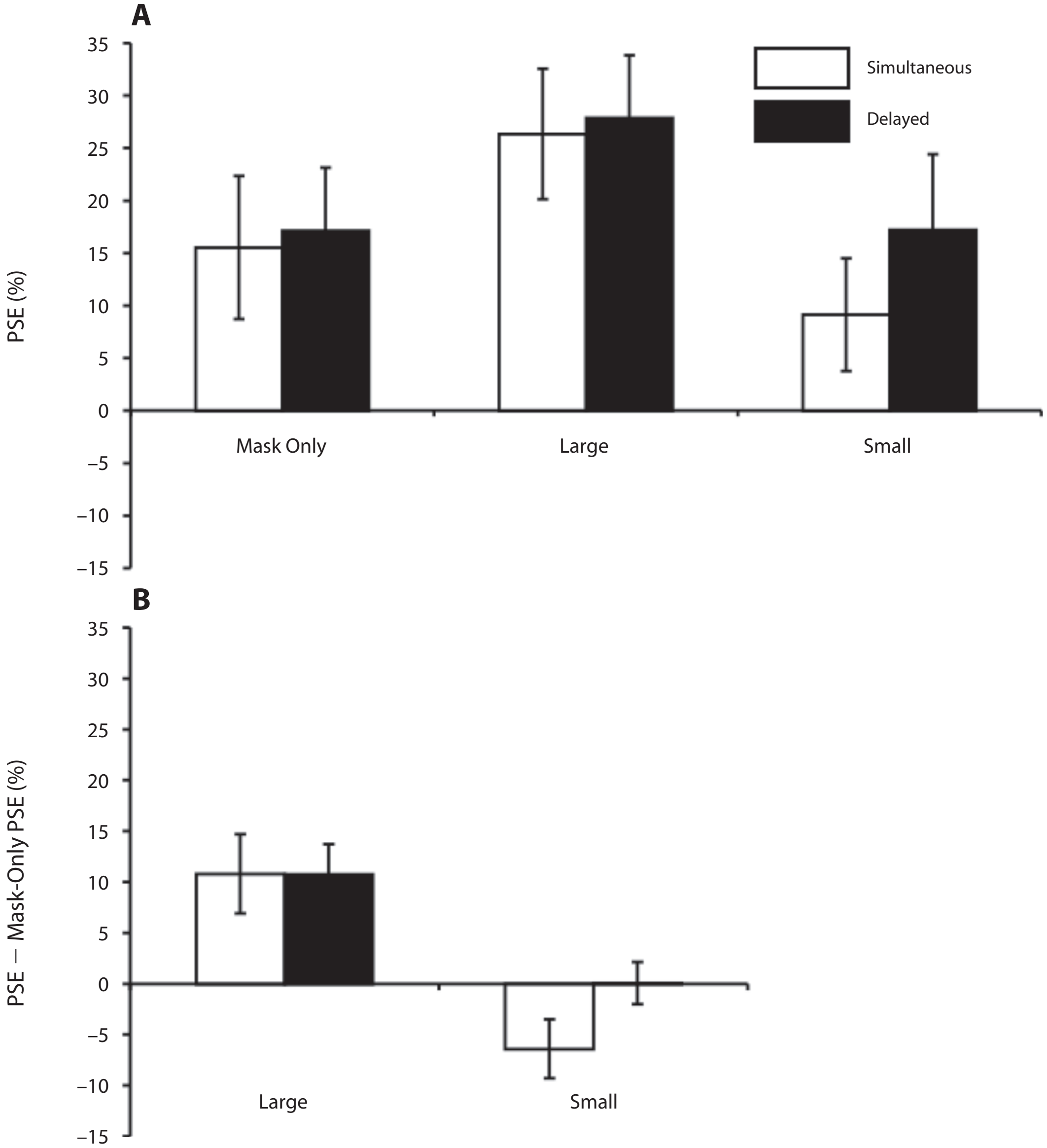

Figure 3. The point of subjective equality (PSE) indicates how much the perceived average size (in terms of proportional diameter) deviated from the actual average size of the circles (excluding the two extra circles presented with four-dot masks). White bars stand for bias in the simultaneous condition, and black bars stand for bias in the delayed condition. (A) The PSE (%) across the circle type × mask type (simultaneous and delayed) conditions. (B) Percentages of the PSE of the large and small conditions were recalculated by subtracting the percentages of the PSE observed in the mask-only conditions. Error bars represent standard errors of the means.

EXPERIMENT 2

In Experiments 1A and 1B, OSM significantly reduced the visibility of the masked circles for most of the participants, but the strength of the OSM effects varied among participants. This observation led to the possibility that the participants showing relatively weak OSM inflated the apparent impact of masked objects on average size judgments. But because separate sets of participants were used for the control experiment (Experiment 1A) testing the visibility of the masked objects and the main experiment on average size judgments (Experiment 1B), we cannot examine the relationship between the OSM strength and the effect of masked circles on average size judgments. If the same participants were used, it would be possible to correlate the strength of OSM in the visibility test with the influence of masked circles on the perceived average size. If the circles less visible because of OSM still participate in the size-averaging process, the participants with both strong and weak OSM (according to the visibility test) should still demonstrate an influence on average size judgments (according to the averaging experiment). In Experiment 2, all of the participants performed both tasks.

Method

Participants. Seventeen undergraduates at Northwestern University participated for course credit or monetary compensation. All of the participants reported normal or corrected-to-normal vision.

Stimuli and Apparatus. The stimuli and apparatus were similar to those in Experiments 1A and 1B, except that instead of employing three different size sets, we used only 0.9º, 1.8º, and 2.4º as target and distractor stimuli during the visibility test. The stimuli used in the average size judgment task were identical to those in Experiments 1A and 1B.

Procedure. To ensure a conservative estimate of OSM, all of the participants completed the 40-min average size judgment phase first and then the 10-min visibility test phase (when practice effects should be at their peak). The procedure was similar to that of Experiments 1A and 1B, but we made several changes in the visibility test. First, we employed only one type of size set (0.9º, 1.8º, and 2.4º). Accordingly, the 0.9º circle was used as the target in the small condition and the 2.4º circle in the large condition. The 1.8º circle served as a distractor.[2] Second, in order to measure discrimination sensitivity (d') of the masked circle's size, we also forced the participants to choose one answer from either "larger than the other circles" or "smaller than the other circles" and eliminated "no percept" from the possible response options. The procedure of the average size judgment task was identical to that in Experiment 1B.

Results and Discussion

Visibility test. One participant was excluded from the analysis because of a strong response bias toward the *smaller* response. The mean accuracy rates of the 16 remaining participants were analyzed with a 2×2 repeated measures ANOVA using two factors: circle and mask type. As was expected, we found a significant main effect of mask type [$F(1,15) = 48.30$, $p < .0001$, $\eta^2 = .76$], suggesting that our OSM procedure could significantly decrease the perceptual quality of the masked object (simultaneous, $M = 93.09\%$, $SE = 1.34\%$; delayed, $M = 80.22\%$, $SE = 2.69\%$).[3] However, there was no significant main effect of circle type or interaction between the two factors [$F(1,15) < 1$, n.s.]. This result suggests that large and small targets are vulnerable to OSM to a similar degree (Figure 4A). We also conducted a paired-samples t test to test for differences in the discriminability between the simultaneous and delayed mask conditions. To avoid infinite d' values, we adjusted both hit rates and false alarm rates by adding a small value to each (Snodgrass & Corwin, 1988). The results showed that the OSM significantly decreased d' [$t(15) = 7.31$, $p < .0001$] (simultaneous condition; $M = 3.16$, $SE = .24$; delayed condition, $M = 2.03$, $SE = .17$; Figure 4B). The criterion C was 0.00 for the simultaneous condition and 0.13 for the delayed condition, suggesting that the participants were slightly biased to respond "small" when the target circle was less visible.

Despite a significant reduction in visibility caused by OSM, the masking procedure could not entirely block conscious perception of the initial circles. The d' for both the simultaneous and the delayed conditions was significantly greater than zero [simultaneous, $t(15) = 13.43$, $p < .0001$; delayed, $t(15) = 11.66$, $p < .0001$].

It may be difficult or impossible to construct an OSM procedure that would perfectly mask object size on every trial. This may be because object size is recovered early in visual processing (Busch & Müller, 2004; Murray, Boyaci, & Kersten, 2006). OSM may be more robust for more complex features that require iterative processing. Typical OSM demonstrations often use more difficult discrimination tasks, such as whether a diamond shape is clipped on the left or right side (Enns & Di Lollo, 1997), letter identification (Enns, 2004; Jiang & Chun, 2001a, 2001b; Reiss & Hoffman, 2006), or shape identification (Woodman & Luck, 2003). In order to perform these tasks, visual information may have to travel to higher visual areas along the ventral pathway, such as LOC (Kourtzi & Kanwisher, 2001), or the visual word-form area (Cohen et al., 2000). As a result, it is highly likely that more processing

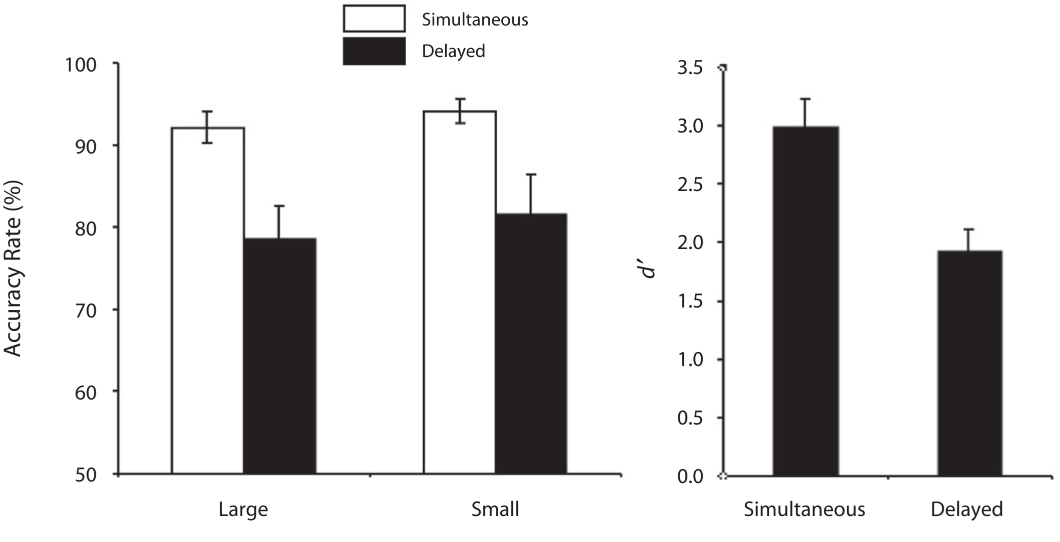

Figure 4. The visibility of the masked circle for the two mask types. (A) White bars indicate accuracy for size identification in the simultaneous condition; black bars do so for the delayed condition. (B) *d′* for the size identification of the masked circle. Error bars represent standard errors of the means.

time is required to complete perceptual consolidation for this type of high-level object discrimination.

Although the OSM manipulation did not entirely block conscious perception of the size of the masked circles, there was a large reduction in visibility. If this visibility reduction reduces the influence of the masked circles during the average size judgment task, we can conclude that size averaging relies primarily on later representations. If this visibility reduction does not affect the contribution of masked circles to the average size judgment, size averaging may have access to a relatively early representation.

Average size judgment. The results were very similar to those in Experiment 1B. There was a general tendency to overestimate average object size [$t(15) = 3.50$, $p = .003$]. To explore the effects of OSM on the size-averaging process, a 3 × 2 repeated measures ANOVA was performed, using the two factors circle and mask type, with Greenhouse–Geisser corrections for sphericity violations in the main effects of both circle type and mask type. The main effect of circle type was significant [$F(1.23, 18.51) = 12.75, p < .0001, \eta^2 = .68$]. This main effect was driven by significant differences between the members of all of the possible pairs: between the large ($M = 25.84\%$, $SE = 4.17\%$) and the mask-only ($M = 12.75\%$, $SE = 3.09\%$) conditions [$t(15) = 5.25$, $p < .0001$], between the small ($M = 10.06\%$, $SE = 3.62\%$) and the mask-only conditions [$t(15) = 2.72$, $p = .016$], and between the large and small conditions [$t(15) = 6.18$, $p < .0001$]. The differences among the three circle conditions indicate that the two extra circle sizes affected the perceived average size. The main effect of mask type was also significant [$F(1,15) = 12.30$, $p = .003$, $\eta^2 = .45$], again showing a tendency of overestimation in the delayed condition ($M = 19.40\%$, $SE = 4.12\%$) relative to the simultaneous condition ($M = 13.04\%$, $SE = 2.89\%$). There was no significant interaction between circle and mask type ($F < 1$, n.s.) (see Figure 5A).

Again, we tested whether the two masked circle sizes affected the perceived average size across the simultaneous and delayed conditions even after subtracting the effect of the four-dot mask independent of the presence of the circles. As in Experiment 1B, we found a significant main effect of circle size [$F(1,15) = 38.19$, $p < .0001$, $\eta^2 = .72$], showing a larger perceived average size in the large condition ($M = 13.09\%$, $SE = 2.49\%$) than in the small condition ($M = -2.69\%$, $SE = .99\%$). Also, we found neither a main effect of mask type ($F < 1$, n.s.) nor a significant interaction between circle size and mask type [$F(1,15) = 1.32$, $p = .27$, $\eta^2 = .08$]. The results suggest that the extra circles participated in the size-averaging process even when their visibility was impaired (see Figure 5B).

Identification sensitivity was significantly reduced by OSM, and masked circles still contributed to the perceived average size as much as circles without OSM. In addition, it is likely that the d' obtained from our visibility test is a conservative measurement of the visibility of masked circles during the average size judgment task. During the visibility test, the masked circle was the only task-relevant object in the display, whereas in the averaging task, all circles were task relevant. Consequently, the participants should have distributed their region of selection more broadly in the average size judgment than in the visibility test (Chong & Treisman, 2005b). Since OSM is strongly under conditions of broader selection (Enns, 2004; Luiga & Bachmann, 2007), it is likely that the masked circles were even less visible during the average size judgment task than during the visibility test. Also, because the visibility test was a two-alternative forced choice, it is possible that the test tapped into subconscious representations. Although the present results cannot support or rule out this possibility, we note that the participants frequently expressed frustration about the extreme difficulty of judging the size of a masked circle during the visibility test.

Because the visibility impairment caused by OSM varied among participants, it is possible that the effects of the masked circles on average size judgments are primarily due to those participants with the weakest OSM. As evidence against this possibility, we conducted two correlation analyses across participants in Experiment 2, comparing the strength of the OSM effect with the contribution of the masked object to the average size judgment. Both of these correlations are visible in Figure 6A.

Figure 6A summarizes the results of both the individual and the average size judgment tasks of each individual participant. The x-axis (visibility) represents the visibility of the masked circle during the visibility test. The y-axis (size estimation bias) represents the difference in the PSE between the large and small extra-circle conditions (e.g., the difference between the white or dark bars in Figure 5B, for the simultaneous or the delayed conditions, respectively). Each arrow represents a participant. The starting points of each arrow mark the values from the simultaneous (non-OSM) condition, and the ending points mark the values from the delayed (OSM) condition. Leftward arrows indicate that the OSM was successful in decreasing the visibility of the enclosed circle. The vertical aspect of arrows represents the impact of OSM on the size-averaging process. Upward arrows indicate an increase in the contribution of masked circles on the average size judgment, and downward arrows indicate a decrease.

In Figure 6A, note that all of the arrows point to the left, suggesting that the OSM manipulation was effective in reducing circle visibility for every participant. However, the arrows do not systematically point downward, which is consistent with the result that size estimation bias was not significantly reduced in the OSM trials. One might point to the three salient downward-pointing arrows (denoted as +), as evidence that less OSM was related to less of an effect of the masked circles on averaging performance. However, note that for those individuals, the decrease in visibility between the simultaneous and delayed conditions was actually quite small. One of these participants showed low d' in general and had a high tendency to overestimate the average size. The other participant with the most downward-pointing arrow actu-

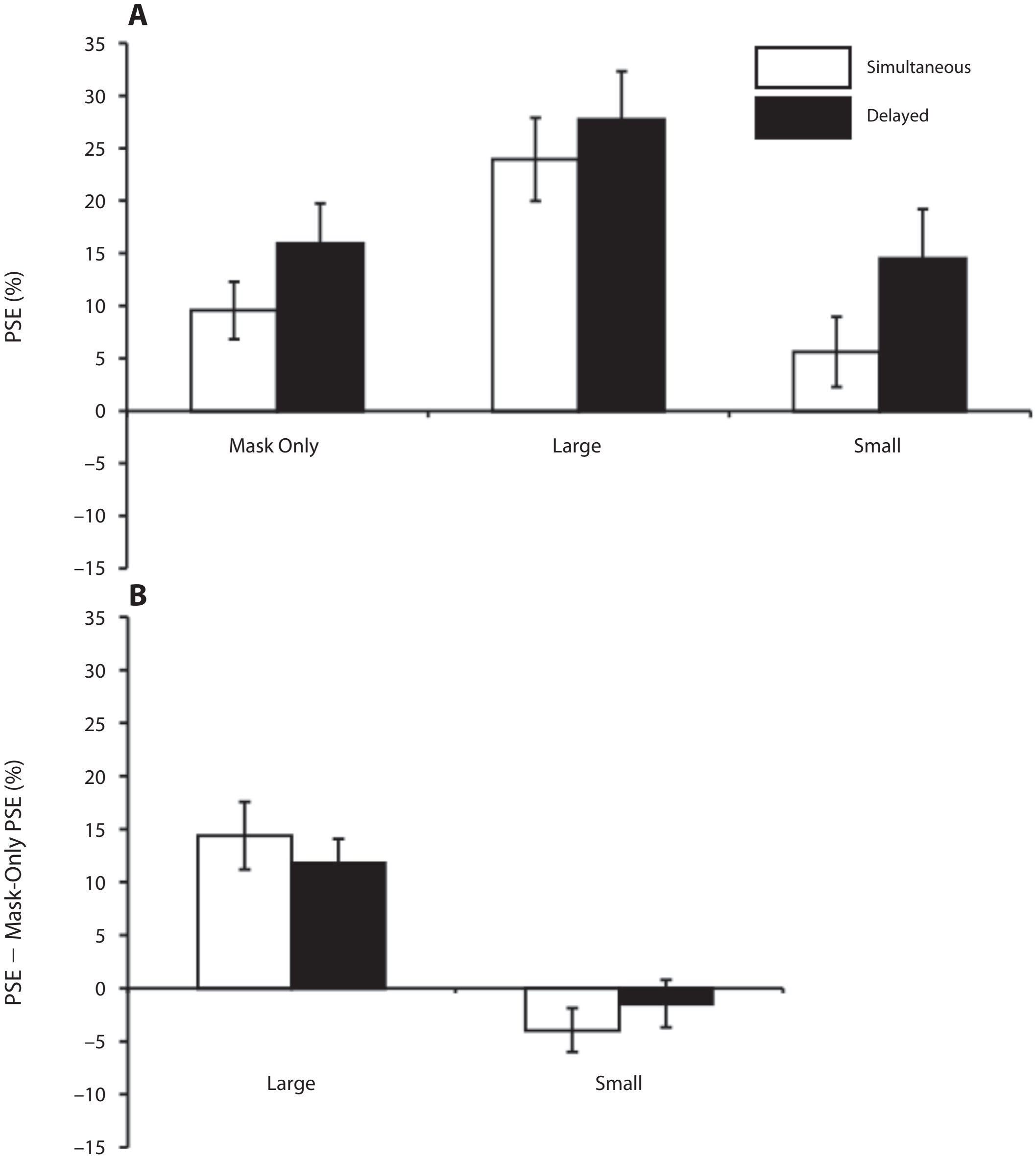

Figure 5. (A) The point of subjective equality (PSE, %) across the circle type × mask type (simultaneous and delayed) conditions. (B) Percentages of the PSE of the large and small conditions were recalculated by subtracting the percentages of the PSE observed in the mask-only conditions. Error bars represent standard errors of the means.

ally showed a relatively small masking effect during the visibility test. In addition, the participants whose visibility of circle sizes dropped the most by OSM do not match those whose perceived average size was affected the most by the masked circles. These patterns, in addition to those of the 13 other participants who did not show such large drops, suggest that there is no correlation between these two factors.

For the first formal correlation across participants, we compared d' for masked circles in the visibility test with the contribution of those masked circles to the average size judgment, as was measured by the PSE difference between trials with large and small extra circles (i.e., the difference between the dark bars in Figure 5B). This correlation can be visualized in Figure 6A by attending to only the arrowheads, while ignoring the arrow lines. There was no significant correlation between the two variables ($r = .01, p = .979$), suggesting that the participants with weaker OSM were not responsible for the influence of masked objects on size-averaging judgments.

As a second correlation measure, we compared the change in d' between the simultaneous and the delayed conditions in the visibility test (the horizontal component of each arrow) with the change in size estimation bias (the

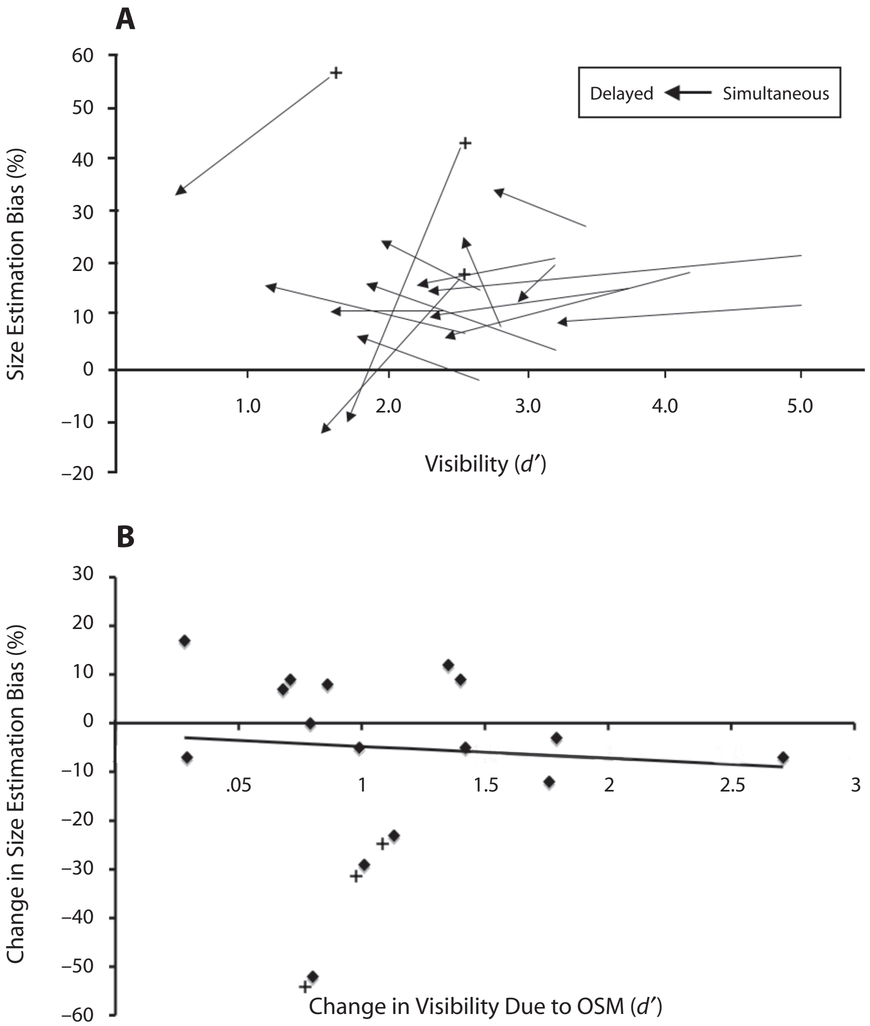

Figure 6. The relationship between the masking effect measured by the visibility test and the influence of the masked circles on the average size estimate. (A) Individual arrows represent how object substitution masking (OSM) affected both the visibility and the perceived average size. The starting point shows the point of subjective equality and *d′* in the simultaneous condition, whereas the ending point shows those in the delayed condition. The 3 participants whose pattern of results deviated from the other participants' were marked by a plus sign (+; see the text). (B) The same relationship expressed as the change in *d′* and the change in OSM effect across the simultaneous and delayed conditions.

vertical component of each arrow), and these difference scores are depicted in Figure 6B. There was again no significant correlation ($r = -.085$, $p = .754$). This result suggests that how much OSM decreased an object's visibility was not related to the decrease in the contribution of those objects to average size judgments.

Note that these correlations were across participants, and necessarily collapsed across trials. It is therefore possible that the PSE measured during delayed trials was not based exclusively on trials where OSM was entirely successful. One solution might be to measure averaging judgment and OSM simultaneously on every trial to obtain a within-subjects correlation across trials. However, this design would require the participants to selectively attend to the masked objects while also making a judgment about the whole collection of objects. This technique would also encourage a strategy by which the participants primarily sample the masked objects to make their size judgment. Although it is possible that a within-subjects correlation would provide a more sensitive measure of the contribution of the masked objects to the size average, the present between-subjects analyses suggest that the result would not differ. The contribution of the two extra circles on the perceived average size was statistically comparable between the simultaneous and delayed conditions, and it is therefore difficult to explain the masked object's large effect with a small portion of trials where the participants saw the masked object.

In summary, the results of Experiment 2 were similar to those of Experiments 1A and 1B, demonstrating that the masked circles influenced the size-averaging process.

In fact, these relatively early representations of objects contributed to average size judgments as much as later representations did. We found no significant correlation between performance on the visibility test and that on the average size judgment task; how well an individual perceived the size of the masked circle in the OSM procedure was not related to how much the two masked circles affect the perceived average circle size. This finding implies that the late representations of individual objects may not be necessary for that object to contribute to an average size representation.

GENERAL DISCUSSION

In this study, we explored the perceptual stage at which average size information arises. In particular, we tested whether relatively early representations participate in the size-averaging process by interrupting processing with OSM. Experiments 1A, 1B, and 2 showed that early object representations contributed to average size judgments even though OSM significantly limited perceptual processing. In each display, there were two large or two small circles masked by OSM. If OSM interfered with a circle's participation in the average, the sizes of the masked circles should not affect estimates. In contrast, we found that estimates of average circle size were larger when the large circles were present than when small circles were present. The contribution of the masked circles was the same as when the circles were clearly visible to the participants. In addition, the effect of the extra masked circles was just as strong for the participants with strong OSM than for those with weak OSM.

Why might size contribute to an average judgment, even under conditions of compromised awareness? It is likely that size is coded at sufficiently early visual stages that size information can still be recovered by the averaging process. Other work on size averaging is consistent with the idea that early representations of objects contribute to the calculation of the average size (Im & Chong, 2009). This study showed that size judgments are modulated by the contrast between the judged objects and the size of nearby flanker objects (i.e., the Ebbinghaus illusion). At first glance, the fact that size averaging is based on more sophisticated representations involving size *contrast* in addition to size alone might indicate that averaging operates over a later representation. But another study showed that size contrast is computed early in visual processing (Busch & Müller, 2004). These findings suggest that representations used to calculate the average size could arise at an early stage of perceptual processing and effectively modulate estimates of the average size even when later representations are impaired.

Mechanisms of Size Averaging

The finding that early representations contribute to the size-averaging process constrains the possibilities for *how* the visual system forms an average representation from these representations. One large category of mechanisms could be labeled *integration fields* over space. According to these accounts, multiple features present in an area of the visual field are processed concurrently and merged into a common representation. For example, in demonstrations of crowding, a target object (such as an oriented grating or letter) is made unidentifiable by adding nearby flanker objects (Bouma, 1970, 1973; Toet & Levi, 1992). Previous studies have suggested that although featural information about the target is recovered at some processing stage, there may be no conscious access to that information, because its features are mandatorily pooled with features from nearby objects.

This crowding effect is thought to reflect integration or pooling of information and not a loss of information. In one study, participants were shown a set of oriented gratings and were required to report whether the overall array appeared tilted clockwise or counterclockwise from the horizontal axis (Parkes, Lund, Angelucci, Solomon, & Morgan, 2001). The participants could still report the tilt direction of the array when a central tilted grating was made invisible because of crowding by flanking horizontal gratings, suggesting that a summary representation of both the central tilt and its flanking gratings aided the participants when performing the identification task. Also, when the participants were required to report the tilt direction of the central grating, performance was affected by the tilt direction of the flanking gratings. When flanking gratings had an opposite tilt direction, which should render an average tilt less informative, the identification of the crowded central target was severely impaired. In contrast, distractor tilts congruent to the target tilt enhanced performance. Both the target and distractor tilt signals appeared to be involuntarily pooled together.

The spatial area where this mandatory pooling occurs is often referred to as an *integration field* (Pelli, Palomares, & Majaj, 2004) or an area of minimum attentional resolution (Intrilligator & Cavanagh, 2001). These fields appear to be smaller near the fovea and larger in the periphery, with a size proportional to their eccentricity (Bouma, 1970; Pelli et al., 2004). These field sizes are congruent with the length of horizontal connections in V1 (Gilbert, Ito, Kapadia, & Westheimer, 2000) and the size of receptive fields in V4 (Desimone & Schein, 1987; Desimone, Schein, Moran, & Ungerleider, 1985; Motter, 2002; Piñon, Gattass, & Sousa, 1998). This finding raises the possibility that average information arises somewhere in the visual cortex through the integration of information by neural connections encompassing nearby spaces or through the pooling of information falling into the same receptive field in a higher visual area.

These studies of crowding explore mandatory pooling of information across small spatial areas. However, a similar pooling process may be available for larger spatial areas when larger parts of the visual field are selected by attention. Pooling with such a voluntarily larger scope could underlie our ability to average information across objects distributed across the visual field.

In one study, participants had to identify or localize the orientation of the most tilted target among slightly tilted distractors (Baldassi & Burr, 2000). Critically, unlike in

Parkes et al. (2001), the objects were not placed close enough to create crowding effects but were instead distributed across the display. Consistent with past results using visual search tasks, the participants localized the target more efficiently when the distractors were tilted in the opposite direction from the target than when they were tilted in the same direction. Indeed, searches are usually more efficient when targets are more distinct from distractors (Duncan & Humphreys, 1989; Treisman & Gelade, 1980). But surprisingly, when the task was to simply identify the direction of tilt for the target, without the need to locate it within the display, the pattern was reversed. Target identification performance was actually better when distractor orientations were more similar to the target orientation. The participants subjectively reported that they used a global sense of tilt to do the task. To explain this puzzling result, the authors argued that orientation signals from the whole display were integrated into an average orientation. If the average orientation was the same as that of the target, a small tilt was enough for the participants to judge the most tilted orientation. If the average orientation was opposite to that of the target, a large amount of tilt was required to judge the target signal. In support of this explanation, when the number of distractors was increased, the effect (either beneficial or detrimental) of distractor orientations increased as a function of the square root of the total set size. This relationship matched a prediction from an account in which an average representation is created by pooling information across objects.

In contrast, when the participants were precued to the location of the most tilted orientation, the influence from the distractor orientation disappeared. If the target could easily be localized with focused attention, there would no longer be a role for pooled representations across all objects in the display. Together, these results suggest that a voluntary diffusion of attention across multiple objects can lead to a summary representation.

This pooling account of perceptual averaging is also consistent with the fact that the size-averaging process operated better with distributed attention rather than focused attention (Chong & Treisman, 2005a). Averaging accuracy was higher (1) when the target from the given display popped out rather than requiring a serial scan, (2) when the secondary task was to identify a global object relative to a local object, and (3) when the objects were presented simultaneously across space rather than sequentially over time. That is, the objects under the same attentional window or the same integration field might be pooled together to form an average representation.

How might information about object size be pooled across objects? One possible mechanism of size coding is spatial frequency channels in visual areas (Chong et al., 2008). Many studies suggest that the structure of hypercolumn cells in V1 resembles a Fourier analyzer, presumably coding the size information within a receptive field (Kulikowski & Bishop, 1981). Studies on scene perception have suggested that spatial frequency profile plays a role in extracting the gist information of the scenes (Oliva & Torralba, 2006). In the average size judgment task, this profile would be affected by circle size, with larger circles adding relatively more power at low frequencies and small circles adding relatively more power at high spatial frequencies. However, some have argued that spatial frequency coding may not be able to explain averaging in typical displays using outline circles, because changing the sizes of outline circles may have little impact on the spatial frequency profile of a display (Myczek & Simons, 2008).

Despite evidence that averaging occurs through participants' broadly selecting an entire collection of objects, recent data have challenged this idea. Instead, the participants might estimate average size by sampling one object or even a few objects. Simulation of an ideal participant shows that such strategies can indeed approximate actual levels of human performance (Myczek & Simons, 2008). These strategies include sampling one or more objects randomly, sampling either the smallest or largest object, or sampling both the smallest and largest objects and computing their mean. Instead of broadly selecting an entire collection, the participants might rely on the strategic application of focused attention directed toward just a subset of objects. One broad division between sampling strategies would be random sampling (e.g., *n* number of objects randomly chosen in a display), and strategic sampling (e.g., the largest or smallest object in a display). Random sampling could potentially explain the systematic influence from the masked circles in our study. The participants would allocate focused attention to random locations among the possible circle locations before the appearance of the circle array. Because preallocating attention to a specific location can reduce the masking effects of OSM (Enns, 2004; Luiga & Bachmann, 2007), the sampled object could influence judgments equally between the simultaneous and delayed conditions. However, this alternative is made less likely by the fact that randomly sampling one object can explain only a small subset of size estimation demonstrations (Ariely, 2008; Chong et al., 2008; Myczek & Simons, 2008; Simons & Myczek, 2008).

It would be more difficult to explain the present results with sampling accounts that employ more sophisticated strategies. If a participant used the strategy of selecting either the smallest or largest object in the display, this selection process would likely require re-entrant processing that should be impaired by OSM. Measuring the effect of masked objects on average size judgments might be a useful future technique for discouraging participants from using this class of sampling strategies.

To conclude, the present results show that a subset of objects with reduced visibility still contributes to the judgment on average size of a collection of objects. The results suggest that early and fragile representations formed in the initial stages of perceptual processing can contribute as much to the size-averaging process as superthreshold representations formed in later stages do.

AUTHOR NOTE

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NOTES

1. Throughout this article, the phrase *masked circle* refers to the circles presented with delayed masks that should lead to OSM but should not imply that the masking effect was always successful on every trial.

2. Although the task was to judge whether the target was larger or smaller than distractors, sizes for all stimuli types were constant, which allowed them to judge on the basis of the absolute size of the masked object without actually comparing it with the distractors. As a result, the participants could perform the task without checking the size of the distractor circles. We expect that the time taken to judge the individual size of the masked circle could be reduced by this modification, allowing a more conservative measure of the visibility of masked circles during the average size judgment.

3. In Experiment 1B, there were three response choices: large, small, or no percept. If the participants had been forced to choose between large and small responses, they would have guessed on no-percept trials, leading to half correct and half incorrect responses. If this were so, we could predict that their performance for the simultaneous condition would have been 84.24% and 71.02% for the delayed condition. Although these values are generally lower than those in Experiment 2, the drop in performance caused by the delayed mask was similar.

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