Cognition 157 (2016) 358–364

Contents lists available at ScienceDirect

Cognition

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

Brief article

Object individuation is invariant to attentional diffusion: Changes in the size of the attended region do not interact with object-substitution masking

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ARTICLE INFO

Article history:
Received 8 April 2016
Revised 7 October 2016
Accepted 10 October 2016
Available online 17 October 2016

Keywords:
Object individuation
Object perception
Visual attention
Visual span
Attentional spotlight size
Object-substitution masking

ABSTRACT

When the human brain is confronted with complex and dynamic visual scenes, two pivotal processes are at play: *visual attention* (the process of selecting certain aspects of the scene for privileged processing) and *object individuation* (determining what information belongs to a continuing object over time versus what represents two or more distinct objects). Here we examined whether these processes are independent or whether they interact. Object-substitution masking (OSM) has been used as a tool to examine such questions, however, there is controversy surrounding whether OSM reflects object *individuation* versus *substitution* processes. The object-individuation account is agnostic regarding the role of attention, whereas object-substitution theory stipulates a pivotal role for attention. There have been attempts to investigate the role of attention in OSM, but they have been subject to alternative explanations. Here, therefore, we manipulated the size of the attended region, a pure and uncontaminated attentional manipulation, and examined the impact on OSM. Across three experiments, there was no interaction. This refutes the object-substitution theory of OSM. This, in turn, tell us that object-individuation is invariant the distribution of attention.

1. Introduction

Imagine you are walking down a city street that is crowded with pedestrians and busy with traffic. In such complex scenes, two critical psychological processes are at play. One is visual attention, the selection mechanism that prevents volumes of information in the scene from overwhelming our limited-capacity processing resources. Visual attention prioritises stimuli that are salient or relevant to our goals for processing while down-weighting the processing of less relevant stimuli. The other is object-individuation inferences. Particular objects in the scenes can move and change their appearance (e.g., due to viewpoint variation), and new objects can replace old objects. Such changes can occur while attention is directed elsewhere. The visual system, therefore, has to infer what information belongs to an object continuing over time (e.g., a car that was previously at one end of the street versus the other at a later time), versus what information belongs to distinct objects (e.g., two different people standing at the bus-stop at different points in time). Such inferences occur non-consciously, but determine conscious perception of the scene. The purpose of this study is twofold: first, to examine whether object-substitution masking is affected by the size of the attended region, thereby resolving an outstanding theoretical controversy in the literature, and second, in light of resolving that theoretical controversy, to therefore examine the interplay between the two fundamental visual-cognitive processes that occur when processing dynamic scenes: attentional selection and object-individuation (Fig. 1).

Object-substitution masking (OSM) has been used as a tool to attempt to answer questions about visual attention and object-individuation. However, this is problematic, because there remains contention about whether OSM reflects *object-substitution* versus *object-individuation*. In OSM, a target is presented briefly surrounded by four small dots arranged in a square. Masking (i.e., an impairment in target perception) occurs when four-dots stay visible briefly after the target has disappeared (delayed mask offset, or trailing mask condition), compared with when the four-dots disappear at the same time as the target (simultaneous mask offset, or 0 ms trailing mask). Masking magnitude is the difference in accuracy between the delayed and simultaneous mask offset trials (Di Lollo, Enns, & Rensink, 2000; for a review see Goodhew, Pratt, Dux, & Ferber, 2013) (see Fig. 2).

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http://dx.doi.org/10.1016/j.cognition.2016.10.006
0010-0277/

Fig. 1. There are two main ways in which humans can regulate the allocation of attentional resources in a visual scene. First, the central point of focus can be moved around to different locations in space. Copious evidence indicates that such attentional shifts can alter response efficiency and perception (Carrasco, 2011; Posner, 1980, 2014), and that not paying attention can lead to dramatic failures of perception (Simons & Chabris, 1999). Second, the *size* of the attended region can be modulated. That is, attentional resources can be concentrated in a small region of space, or they can be spread more broadly over a larger area. When specific attentional region sizes are induced experimentally via stimuli and/or task demands, they have powerful effects on response efficiency (Benso, Turatto, & Gastone, 1998; Castiello & Umiltà, 1990; LaBerge, 1983), perceptual acuity (Goodhew et al., 2016), and neural responsivity (Muller, Bartelt, Donner, Villringer, & Brandt, 2003). The above picture illustrates an example of a small versus large attended region size applied in a visual scene. Stimuli that fall within the scope of the region are 'attended', whereas stimuli that fall outside of the scope are not attended.

Initially OSM was attributed to a process whereby the object representation for the four-dots alone (the temporally-trailing mask) *substituted* the preliminary target representation via re-entrant processing (object-substitution account, Di Lollo et al., 2000; Kahan & Lichtman, 2006; Weidner, Shah, & Fink, 2006). According to this *object-substitution* account, preventing focussed attention on the target is a critical factor in promoting object-substitution. However, since then, it has been proposed that masking actually reflects object-updating, whereby the representation of the target is *updated* to reflect the four-dots alone (Goodhew, Boal, & Edwards, 2014; Goodhew, Edwards, Boal, & Bell, 2015; Guest, Gellatly, & Pilling, 2012; Lleras & Moore, 2003; Luiga & Bachmann, 2008; Moore & Lleras, 2005; Pilling & Gellatly, 2010). That is, according to the *object-updating* account, OSM reflects the visual system's inference that the trailing four-dot mask alone is a continuation of the target array, and thus updates the representation that initially contained target-related information target to reflect only the four-dot mask. This account predicts that masking is strongly increased by manipulations that encourage, and reduced by manipulations that discourage the inference the target and mask reflect a continuing object over time. Consistent with this, when the target and mask appear in the same versus different features (such as colours) it exacerbates and mitigates masking respectively (Goodhew et al., 2015; Luiga & Bachmann, 2008; Moore & Lleras, 2005; Pilling & Gellatly, 2010). Similarly, preview of the four-dot masks or placeholder objects at the locations of targets and distractors reduce masking, even when these are neither predictive of target location nor reveal key target features (such as the side of the gap) (Gellatly, Pilling, Carter, & Guest, 2010; Guest et al., 2012; Lim & Chua, 2008). Such manipulations facilitate the system characterising the target and mask as distinct objects. Finally, OSM interacts with repetition blindness (Goodhew, Greenwood, & Edwards, 2016), a phenomenon well-established to gauge inferences of object-individuation (Goldfarb & Treisman, 2011; Kanwisher, 1987; Kanwisher & Potter, 1989), pointing to common mechanisms underlying these two processes.

While there is evidence in favour of the object-updating account, a critical point of differentiation between object-substitution and object-updating remains unresolved. That is, a defining difference between the two accounts is regarding the role of attention: according to object-substitution, visual attention plays a pivotal role in degrading the quality of the initial target representation, thus rendering it vulnerable to substitution. Moreover, the interaction between attention and masking magnitude is touted as the "hallmark" of OSM (Di Lollo et al., 2000). Indeed, the effect of attention was encoded as a key parameter in early computational models of object-substitution (Di Lollo et al., 2000). Object-individuation, in contrast, does not hinge on the effect of attention. Instead, dynamic objects and scenes are sufficiently challenging to induce ambiguity about object continuation versus individuation. The role of attention in OSM has been hotly debated and remains unresolved.

In OSM, typically 'attention' has been manipulated indirectly via set-size, that is, the number of non-target items presented concurrently with the target, with the aim of preventing attention being focussed on the target location. When OSM was first introduced into the literature, preventing focussed attention applied to the target was considered a necessary condition for masking to be observed, and the interaction between set-size and the duration of the trailing mask on target perception was touted as a hallmark of OSM and the substitution processes initially believed to underlie masking (Di Lollo et al., 2000; Goodhew, Dux, Lipp, & Visser, 2012). The interaction was such that masking magnitude was essentially zero when the target was presented alone without non-targets, whereas it increased progressively as set-size increased. Such an interaction suggests that attentional processes are intrinsic to OSM (see Fig. 3).

Years later, however, Argyropoulos, Gellatly, Pilling, and Carter (2013) challenged the validity of this interaction between set-size and mask duration, and therefore the role of attention in OSM. These authors argued that the previous demonstrations of an interaction were an erroneous artefact of floor and ceiling effects containing performance, and showed that when steps were taken to mitigate such constraints, the interaction was eliminated. Furthermore, a number of demonstrations of robust masking when the target was presented alone (Dux, Visser, Goodhew, & Lipp, 2010; Filmer, Mattingley, & Dux, 2015) and finding that providing participants with advance warning about the location of the target also does not modulate masking magnitude (Pilling, Gellatly, Argyropoulos, & Skarratt, 2014) further emphasised that attention may play no role in OSM.

Most recently, however, Camp, Pilling, Argyropoulos, and Gellatly (2015) found that only when the non-targets were more tightly packed around the target (conducive to visual *crowding*), was masking magnitude impacted by the presence of distractors. Camp et al. (2015) attributed this finding to partially shared mechanisms between OSM and visual crowding. Another possibility, however, is that the manipulation of proximity between the target and non-target items indirectly impacted the size of the attended region. In other domains, evidence suggests that increasing the density of items in a target array decreases the size of the attended region (Goodhew & Clarke, 2016). It has also been suggested, however, that a more diffuse attentional state *benefits* target perception in OSM (Prime, Pluchino, Eimer, Dell'Acqua, & Jolicoeur, 2011). This

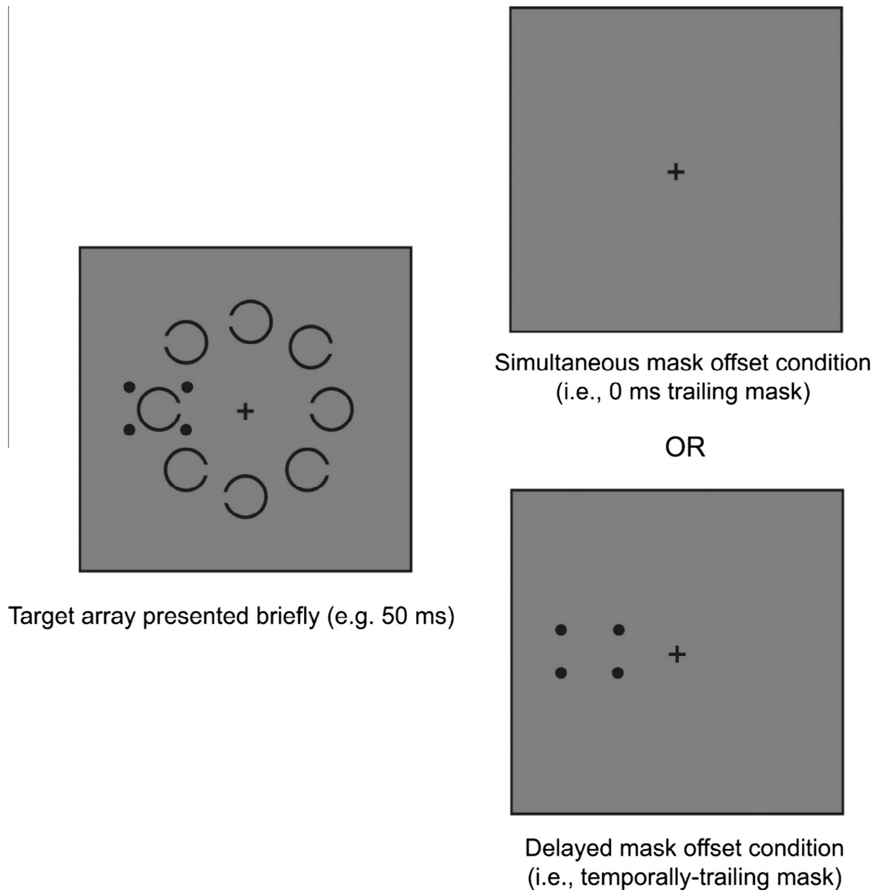

Fig. 2. An example illustration of an object-substitution masking (OSM) display. The target array is presented briefly, followed by one of two possibilities: either all the stimuli in the target array disappear simultaneously (simultaneous offset condition), or all except for the four-dots disappear (delayed mask offset or temporally-trailing mask condition). The four-dots would typically be shown for just a fraction of a second (e.g., 200 ms) before disappearing. This delayed offset of the four-dots impairs target perception (i.e., creates 'masking'), despite the fact that the target and four-dot 'mask' never occupy overlapping spatial locations (unlike e.g., backward pattern masking). Target perception is usually gauged via accuracy at target identification (e.g., which side was the gap in the target, left versus right?). Masking magnitude is the difference in accuracy between the simultaneous and delayed mask offset conditions.

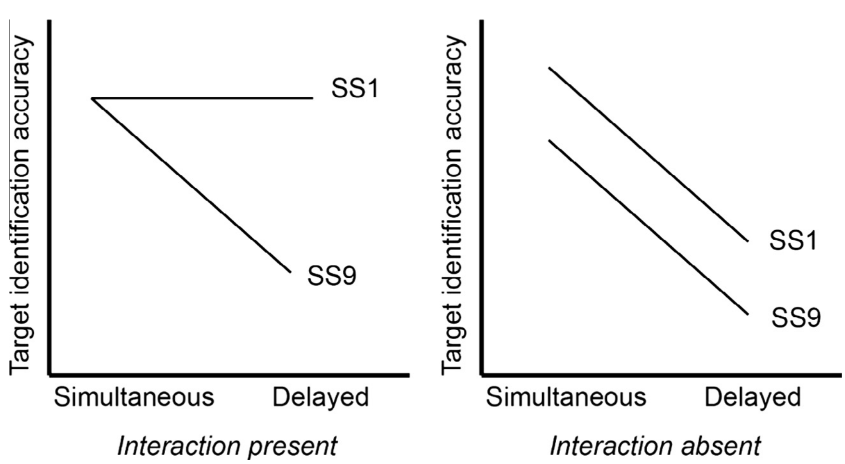

Fig. 3. An illustrative example of the presence and absence of an interaction between set-size (the number of items in the target display, both target + non-targets), and trailing mask duration (where simultaneous offset = 0 ms trailing mask, and delayed mask offset = non-zero trailing mask, example duration = 200 ms). Note that the absence of an interaction does not preclude an overall main effect of set-size, such that overall accuracy is lower at greater set-sizes (and indeed this has typically been observed when the interaction is absent), but the interaction is specifically about the steepness of the slopes between the masking conditions, not overall accuracy. SS1 = set-size 1; SS9 = set-size 9.

is difficult to reconcile with the finding that OSM is exacerbated at larger set-sizes for crowded items. Given this mixed evidence in the literature about the putative effect of the size of the attended region OSM, and the importance of having a clear answer to this question, here, we sought to directly establish the impact of different attended-region sizes on target perception and masking magnitude in OSM. This will have two-pronged significant implications: one, it could resolve the ongoing debate about theoretical

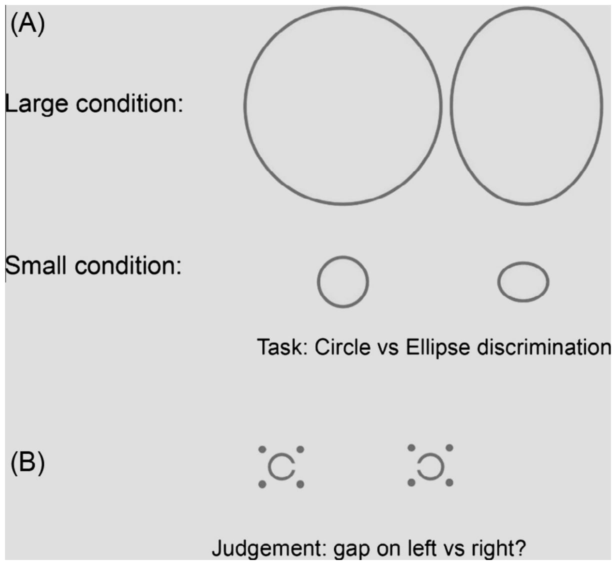

Fig. 4. (A) An illustration of the small and large inducer stimuli, which were either circles or ellipses. Participants' task was to judge whether a circle or ellipse was presented. In Experiments 1 and 3, the ellipse was always shorter than the circle on the vertical dimension, whereas in Experiment 2 the ellipse could be shorter on either the vertical or horizontal dimension. Stimuli were always centred on fixation. Participants performed this task on 80% of trials in a given block. (B) Target stimuli in the OSM paradigm. Participants' task was to identify whether the spatial gap in the circle appeared on the left or right of the centrally-presented object. Participants performed this task on 20% of trials in a given condition (small versus large).

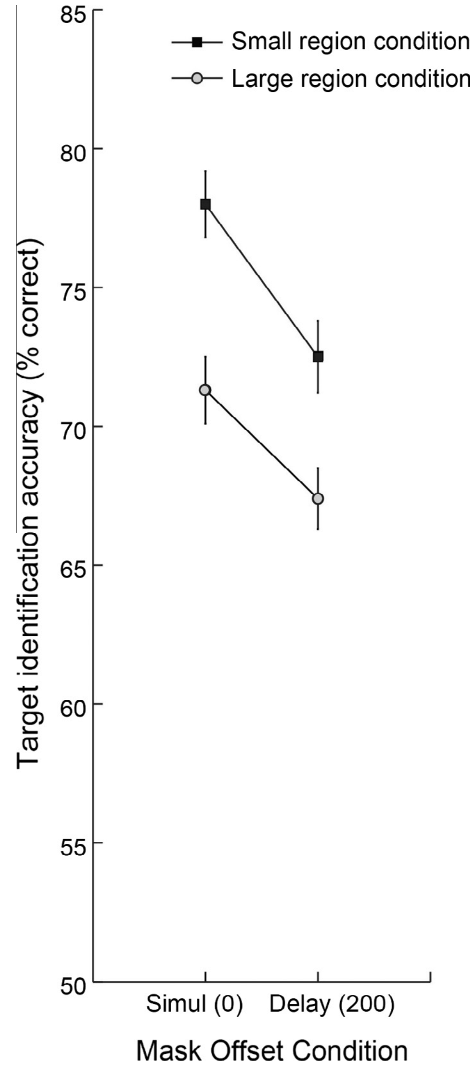

Fig. 5. Target identification accuracy (% correct) as a function of induced attended-region size (small versus large) and mask offset condition (simultaneous offset; 0 ms trailing mask versus delayed mask offset; 200 ms trailing mask). Despite main effects of both attended-region size and mask-offset condition, there was no interaction. Error bars represent standard errors corrected for repeated-measures designs (Cousineau, 2005). While these group means are well clear of ceiling or floor, to confirm that the present results were not a consequence of floor or ceiling effects at the individual level, we repeated the analysis excluding participants whose average target identification accuracy fell below 60% or exceeded 90%. The results with the remaining 27 datasets were equivalent: a main effect of attended-region size ($p = 0.012$, $\eta_p^2 = 0.218$), a main effect of mask-offset condition ($p = 0.006$, $\eta_p^2 = 0.257$), and no interaction ($p = 0.312$, $\eta_p^2 = 0.039$). This indicates that the results were not a product of floor or ceiling effects.

mechanism underlying OSM: individuation versus substitution. Two, if the evidence supports object-individuation, it will inform us whether the two fundamental processes that allow us to navigate complex, dynamic scenes, object individuation and visual attention, are independent or interactive.

2. Experiment 1

The purpose of the present study was to test the relationship between attended-region size and OSM. To manipulate the size of the attended region (attended-region-size), we used a shape-induction method from previous research (Goodhew, Shen, & Edwards, 2016; LaBerge, 1983), which requires participants to respond to stimuli that are blocked to be either small or large diameter and therefore induce a small versus large attended region respectively. Participants complete this task on 80% of trials in a given block, and then the effect of the induced attended-region size is measured on the remaining 20% of trials (randomly intermixed) in which participants complete a second task to measure the effect of the induced attended-region size. Here, that task was a standard OSM paradigm. Masking magnitude is the difference in target identification accuracy between simultaneous and delayed mask offset condition. A statistical interaction between attended-region-size and masking magnitude on target identification accuracy would indicate that the size of the attended region moderates OSM.

2.1. Method

2.2.1. Participants

Forty participants (25 female, 15 male) volunteered for the study in exchange for course credit or payment. Their mean age was 22.23 years (SD = 8.75). In this and subsequent experiments, all participants provided written informed consent prior to participation.

2.2.2. Stimuli and apparatus

The background was set to mid-grey, and the stimuli were darker grey than the background (30% contrast). Inducer stimuli consisted of either small-diameter outline circles and ellipses (small region condition) or large-diameter circles and ellipses (large region condition). The large-diameter circles were 20° of visual angle in diameter, and the ellipses subtended 20° on the horizontal dimension and 16° on the vertical dimension. The small-diameter circles subtended 1°, whereas the ellipses subtended 1° horizontally and 0.8° vertically. The stroke width of the outline circle/ellipses was 0.14°. Targets were outline circles subtending 0.4° (stroke width = 0.07°), with a small (0.04°) gap on the left or right of the object. The four-dots constituting the mask were arranged on the corners of an imaginary square, and each dot subtended 0.14° and was separated from the target by 0.11° (see Fig. 4). The target always fitted within the bounds of the small inducer. To ensure that we purely manipulated attended-region-size in the absence of any shifts of attention, all stimuli (both inducers and targets) were presented centred on fixation. Previous research tells us that attended-region size can be effectively modulated under these conditions (Goodhew, Shen, et al., 2016), and that reliable OSM can be obtained (Filmer et al., 2015).

2.2.3. Procedure

The manipulation of small versus large inducer condition blocked, whereas the assignment of circles versus ellipse stimuli on a given trial were randomly intermixed within blocks. Inducer trials comprised 80% of trials (randomly intermixed) in each small versus large condition block, whereas target trials comprised the remaining 20% of trials. Order of block completion (small versus large) was counterbalanced across participants.

On each trial, the white fixation dot was presented centrally for 253 ms, followed (depending on trial type) by either the inducer stimulus (circle or ellipse) for 53 ms, or the target for 93 ms. On half of the target trials, the four-dots disappeared simultaneously with the target (simultaneous mask offset condition; 0 ms trailing mask), whereas on the other half of trials, the four-dots alone were presented for a further 200 ms after the target (delayed mask offset condition; 200 ms trailing mask). On the inducer trials, participants' task was to identify whether a circle or ellipse was presented, whereas on the target trials, it was to identify whether the target circle had a small spatial gap on its left or its right side. Response keys were 'z' and '/' for circle/ellipse and left/right. Accuracy rather than speed of response was emphasised. After response, the screen was blank for a 1000 ms intertrial-interval. Each condition (small versus large) consisted of 300 trials, and thus the total number of trials in the experiment was 600, with self-paced rest-breaks offered every 150 trials.

Each testing session began with a practice block of 20 trials, where the division between inducer/target trials was 60/40 instead of 80/20. This was to ensure that participants had adequate exposure to the target stimuli during practice. To help familiarise participants with the stimuli, the presentation parameters were initially slowed down and sped up progressively across the practice block. Participants were provided with trial-by-trial visual feedback on the accuracy of their response during practice. To successfully complete practice, participants needed to score greater than 75% on both the inducer and target task (repeated as necessary).

2.2. Results & discussion

Data from one participant was excluded from the analysis because they performed below chance (50%) on this task. For the remaining 39 participants, inducer identification accuracy was high (96% for the small inducers and 97% for the large inducers).

Target identification accuracy data for the remaining 39 participants were submitted to a 2 (attended-region-size: small versus large) × 2 (mask offset condition: simultaneous versus delayed) repeated-measures ANOVA. This revealed a significant main effect of attended-region size, $F(1,38) = 12.10$, $p = 0.001$, $\eta_p^2 = 0.241$, such that accuracy was higher in the small size versus large condition. This demonstrates that the manipulation of attended-region size was successful. There was a significant main effect of mask-offset condition, $F(1,38) = 15.36$, $p < 0.001$, $\eta_p^2 = 0.288$, whereby target identification was greater on the simultaneous than on the delayed mask-offset trials. This demonstrates the presence of OSM. However, there was no reliable interaction between attended-region-size and mask-offset condition, $F(1,38) = 0.48$, $p = 0.494$, $\eta_p^2 = 0.012$. This tells us that the effect of mask offset condition on target identification was unchanged by attended-region size. The absence of an interaction between the two factors of attended-region size and mask-offset condition, which had reliably main effects in their own right, suggests that attended-region size does not affect OSM (see Fig. 5).

3. Experiment 2

The purpose of Experiment 2 was to experimentally replicate Experiment 1 to confirm that the absence of an interaction.

3.1. Method

All other aspects of the methods were identical to Experiment 1 except as specified. Target contrast was reduced in order to make the task more difficult with the aim of increasing the magnitude of effects. Forty participants (20 female, 20 male) (Mean age = 22.68 years, SD = 4.12) completed the experiment.

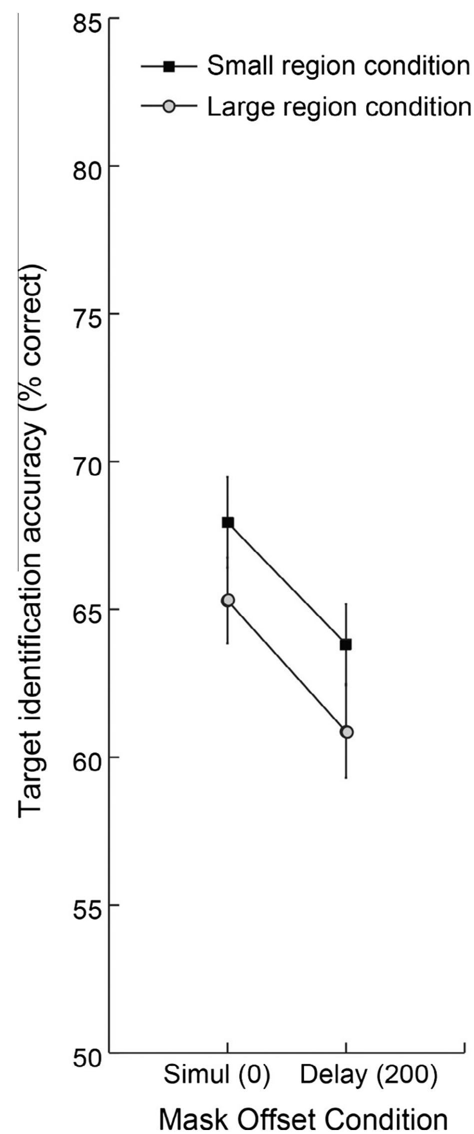

Fig. 6. Target identification accuracy (% correct) as a function of induced attended-region size (small versus large) and mask offset condition (simultaneous offset; 0 ms trailing mask versus delayed mask offset; 200 ms trailing mask). There was no interaction. Error bars represent standard errors corrected for repeated-measures designs (Cousineau, 2005). Again, to check that the absence of the interaction was not constrained by floor or ceiling effects, we excluded any participant whose average accuracy was below 60% or above 90%. This revealed still a trend toward a main effect of attended-region-size, $F(1,20) = 3.03$, $p = 0.097$, $\eta_p^2 = 0.131$, a main effect of mask-offset condition, $F(1,20) = 11.12$, $p = 0.003$, $\eta_p^2 = 0.357$, and no interaction ($F < 1$).

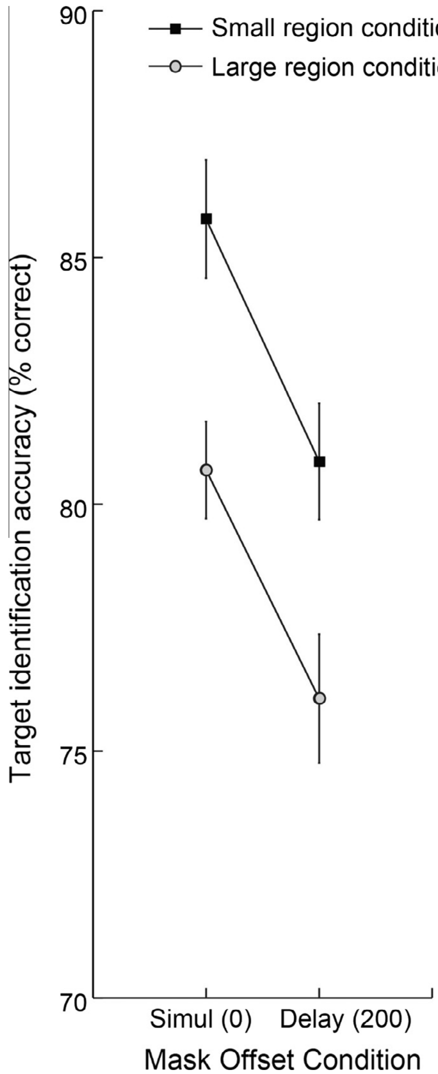

Fig. 7. Target identification accuracy (% correct) as a function of induced attended-region size (small versus large) and mask offset condition (simultaneous offset; 0 ms trailing mask versus delayed mask offset; 200 ms trailing mask). Error bars represent standard errors corrected for repeated-measures designs (Cousineau, 2005). Once more, to check that the absence of the interaction was not constrained by floor or ceiling effects, we excluded any participant whose average accuracy was below 60% or above 90%. The results remained unchanged: a main effect of attended-region-size, $F(1,31) = 7.47$, $p = 0.010$, $\eta_p^2 = 0.194$, a main effect of mask-offset condition, $F(1,31) = 12.41$, $p = 0.001$, $\eta_p^2 = 0.286$, and no interaction $F(1,31) = 0.008$, $p = 0.929$, $\eta_p^2 < 0.001$. *Combined Analysis*. The fact that we have conducted three separate experiments under similar conditions affords the opportunity of combining the data into a single analysis for increased power. Here, therefore, we submitted the target identification accuracy data from the three experiments to a 3 (experiment) × 2 (attended-region-size) × 2 (mask-offset condition) mixed ANOVA. This revealed a significant main effect of attended-region-size, $F(1,110) = 21.27$, $p < 0.001$, $\eta_p^2 = 0.162$, which did not interact with experiment ($F < 1$), and a main effect of mask offset condition, $F(1,110) = 31.43$, $p < 0.001$, $\eta_p^2 = 0.222$, which did not interact with experiment ($F < 1$). Finally, there was still no hint of an interaction between attended-region-size and mask-offset condition, with the F value not even approaching 1: $F(1,110) = 0.134$, $p = 0.715$, $\eta_p^2 = 0.001$. This interaction also did not interact with Experiment ($F < 1$). This means that across all 3 experiments, there were robust effects of size of the attended region and mask offset condition, and absolutely no interaction. Notably, the effect-size for the interaction approached zero.

3.2. Results & discussion

Performance on the inducer task was high (93% and 95% for the small and large conditions). Six participants were excluded for poor target-identification performance: five had average accuracies approximating chance-level performance (51% or below), and one had extremely poor accuracy in a single condition (35%). The mean levels of accuracy in each condition are shown in Fig. 6. Submitting the data to the same analysis as Experiment 1, there was a trend toward a main effect of attended-region-size, $F(1,33) = 2.87$, $p = 0.099$, $\eta_p^2 = 0.080$, a significant main effect of mask-offset condition, $F(1,33) = 5.41$, $p = 0.026$, $\eta_p^2 = 0.141$, and absolutely no hint of an interaction ($F < 0.010$, $p = 0.922$, $\eta_p^2 < 0.001$). However, this result is somewhat ambiguous with only a trend toward a main effect of region-size. Therefore, in Experiment 3, task-difficulty was decreased.

4. Experiment 3

4.1. Method

Experiment 3 was identical to the previous experiments, except that now target contrast was increased to 40%. Forty participants (26 female, 14 male) completed the experiment (mean age = 22.4 - years, SD = 3.6).

4.2. Results & discussion

Inducer task accuracy was high (97% for both conditions). Target identification results are shown in Fig. 7. There was a significant main effect of attended-region-size, $F(1,39) = 8.13$, $p = 0.007$, $\eta_p^2 = 0.173$, a significant main effect of mask-offset-condition, $F(1,39) = 15.12$, $p < 0.001$, $\eta_p^2 = 0.279$, and no interaction, $F(1,39) = 0.020$, $p = 0.889$, $\eta_p^2 = 0.001$.

5. General discussion

Here, across three experiments, we found a reliable impact of both the size of the attended region and OSM on target identification performance, but no interaction between these two variables. This indicates that the size of the attended region neither exacerbates nor mitigates masking by object substitution. Within the OSM context, this finding is the final nail in the coffin for the object-substitution account (Di Lollo et al., 2000), which espouses that attention fundamentally moderates OSM. This evidence instead favours the object-updating model which does not have this requirement. In light of this key finding, plus the previous evidence in favour of the object-updating account, we can interpret OSM as reflecting object-individuation processes across time. This means that the present results imply that object-individuation processes are independent of changes in the size of the attended region. This tells us that as our brains are confronted with dynamic input over time, the relative size of the region we are attending to does not impact the inference about whether to form individual or continuing object identities.

In conclusion, across three experiments, the size of the attended region, despite having a demonstrable effect on overall target perception, did not interact with OSM magnitude. This is inconsistent with the object-substitution theory of OSM, instead favouring the object-individuation account. This, in turn, suggests that object-individuation inferences are independent of the current size of the attended region.

Acknowledgements

This research was supported by an Australian Research Council (ARC) Discovery Early Career Research Award (DE140101734) awarded to S.C.G., and an ARC Discovery Project (DP110104553) grant awarded to M.E. The authors thank Reuben Rideaux, Anne Wentworth-Perry, Samantha O'Brien and Stephanie Kindon for assistance with the data collection. Correspondence regarding this study should be addressed to Stephanie Goodhew (stephanie.goodhew@anu.edu.au), Research School of Psychology, The Australian National University.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cognition.2016.10.006.

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