Amodal completion in visual working memory

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Abstract

Amodal completion refers to the perceptual ‘filling-in’ of partly occluded object fragments. Previous work has shown that object completion occurs efficiently, at early perceptual stages of processing. However, despite efficient early completion, at a later stage, the maintenance of complete-object representations in visual working memory (VWM) may be severely restricted due to limited mnemonic resources being available. To examine for such a limitation, we investigated whether the structure of to-be-remembered objects influences what is encoded and maintained in VWM using a change detection paradigm. Participants were presented with a memory display that contained either ‘composite’ objects, i.e., notched shapes abutting an occluding square, or equivalent unoccluded, ‘simple’ objects. The results showed overall increased memory performance for simple relative to composite objects. Moreover, evidence for completion in VWM was found for composite objects that were interpreted as globally completed wholes, relative to local completions or an uncompleted mosaic (baseline) condition. This global completion advantage was obtained only when the ‘context’ of simple objects also supported a global object interpretation. Finally, with an increase in memory set size, the global object advantage decreased substantially. These findings indicate that processes of amodal completion influence VWM performance until some overall-capacity limitation prevents completion. VWM completion processes do not operate automatically; rather, the representation format is determined top-down based on the simple object context provided. Overall, these findings support the notion of VWM as a capacity-limited resource, with storage capacity depending on the structured representation of to-be-remembered objects.

Keywords: amodal completion, visual working memory, mnemonic resources, context, capacity.

Visual environments provide a cluttered and complex input to the visual system, which must be structured, that is, perceptually grouped into coherent patterns or wholes to support object recognition and visually guided actions. Under natural viewing conditions, many objects in our ambient array are partly occluded by other objects. These occlusion relationships, however, do not result in a percept of fragmented objects; instead, we usually perceive a world that is made out of coherent wholes. For example, in a visual scene, flowers may be hidden behind trees, while a house may in turn occlude parts of the trees. Despite these partial occlusions, we do not perceive the flowers as floating in the air or the trees as having house-shaped holes. Instead, the environment appears to consist of complete objects, and we do almost never experience any ambiguities. The phenomenon that occluded parts are perceptually 'filled in' has been referred to as amodal completion (Michotte, Thines, & Crabbe, 1964/1991), that is, completion in face of the partial absence of physical stimulation.

Two different types of completion have been proposed to account for how people complete partly occluded objects. In global completion, the symmetry of a completed shape is maximized (Sekuler, Palmer, & Flynn, 1994; Van Lier, Leeuwenberg, & Van der Helm, 1995); local completion, by contrast, comprises a 'good' (e.g., linear) interpolation of the occluded contours, yielding an integrated object based on the shape's boundaries (Kellman & Shipley, 1991; Fantoni & Gerbino, 2003). Previous studies have shown that global completion is usually the predominant mode for partly occluded objects (e.g., Sekuler, 1994; Sekuler et al., 1994; Van Lier, 1999, 2001; Van Lier & Wagemans, 1999; De Wit & Van Lier, 2002). However, in addition to global and local completion interpretations, partly occluded objects could also be interpreted as an uncompleted two-dimensional 'mosaic' figure. That is, a mosaic interpretation would be the most basic one, simply taking the visible input as a default: the figure is simply represented in terms of the visible, 'cut-out' segments that adjoin one another, without considering that parts of the object may be occluded. Figure 1 provides several examples of global, local, and mosaic completions, illustrating that every partly occluded figure may give rise to different complete-object or corresponding mosaic interpretations.

A number of studies employed visual search paradigms to investigate whether integrated object representations are available pre-attentively. For instance, it has been shown that visual search for a partly occluded target is guided by a complete-object representation (He & Nakayama, 1992; Rensink & Enns, 1998; Davis & Driver, 1998). For example, in Rensink and Enns (1998), participants searched for a notched disk target among complete disks and squares. In a condition in which the notched target disk abutted a square (adjacent condition), the search turned out inefficient – because, so the explanation, the notched target is rendered similar to the complete distractor disks by amodal completion. In contrast, search was efficient when the target was spatially separated from the neighboring square; in this (separate) condition, completion does not occur – thus supporting more efficient search. Results such as these have been taken to indicate that visual search relies on complete-object representations (see also Conci, Müller, & Elliott, 2007a; 2007b; 2009), with (amodal) completion occurring rather automatically, that is, prior to the engagement of attention (Mattingley, Davis & Driver, 1997; Conci et al., 2009). However, Rauschenberger and Yantis (2001), in a follow-on study, combined a search task with a masking procedure to interrupt visual processing. Given sufficient time prior to masking, the previous results were replicated, that is: there was evidence of amodal completion in the adjacent condition, but not in the separate condition. By contrast, when the masks were presented relatively early (< 200 ms), search was comparable in efficiency between the separate and adjacent conditions, indicating that, under these conditions, amodal completion was prevented with the adjacent configuration. This outcome suggests that completion goes through distinct stages and that an initial, “mosaic” stage may precede completion (see also Sekuler & Palmer, 1992; Plomp, Liu, Van Leeuwen, & Ioannides, 2006).

Taken together, these findings indicate that completed objects are processed rather efficiently, with sequential perceptual stages rendering completed objects starting from a simple, default ‘mosaic’ interpretation. However, at an even later stage of processing, the encoding and maintenance of object representations in visual working memory (VWM) may be tightly restricted due to the limited availability of mnemonic resources (Jolicoeur & Dell’ Acqua, 1998; Thorpe, Fize, & Marlot, 1996; Vogel, Luck, & Shapiro, 1998; Woodman, Vogel, & Luck, 2001). Here, we investigated whether the structure of to-be-remembered objects influences what is encoded and maintained in VWM.

Specifically, in this study, we were interested in whether completion is reflected in memory capacity. Luck and Vogel (1997) showed that VWM can roughly store about four items, irrespective of the number of features that the objects are composed of; restated, VWM may be conceived of as providing about four “slots”, permitting up to four complete objects to be represented irrespective of their complexity. However, subsequent evidence indicated that VWM capacity in fact also depends on visual information load, rather than reflecting just the number of objects currently held in VWM. For example, Alvarez and Cavanagh (2004) attempted to characterize the visual information load of different objects categories (such as shaded cubes, Chinese characters, and colored squares) in terms of the search efficiency afforded by each object category in a simple visual search task (under conditions of varying search display sizes). The assumption was that search efficiency (i.e., the slope of the function relating display size to response latency) would reflect the perceptual complexity of a given object category. In a subsequent experiment, the same objects were presented in a change detection task, which required participants to remember a set of objects in an initial memory display. Then, following a brief delay, a test display was presented which required participants to determine whether one of the presented objects, which were all of the same category, had changed. The results revealed a strong linear relation between the number of items that can be stored in VWM (as assessed in the change detection task) and the visual information load of these items (as determined by the slope of the search function). According to this logic, if a completed object is represented in VWM, memory capacity should be affected, because post-completion representations give rise to a greater visual information load (as evidenced by steeper slopes) in visual search studies compared to uncompleted objects (He & Nakayama, 1992; Rensink & Enns, 1998; Davis & Driver, 1998). Following this line of reasoning, we hypothesized that completion requires mnemonic resources, that is: completed objects require more VWM capacity to be maintained, leading to reduced memory performance if capacity is exceeded.

To test this idea, we employed a change detection paradigm (Luck & Vogel, 1997) in which participants were presented with a memory display that contained composite objects (i.e., a notched-figure adjacent to a square) or simple objects (i.e., possible interpretations of the composite objects without the adjacent square, see Figure 1). After a brief delay, a simple object probe appeared, presenting one possible interpretation at one of the locations that had previously been occupied by an item in the memory display. The task was to decide whether the probe item was the same as or different from the object presented beforehand at the same location in the memory display (see Figure 2 for an example). This variant of the change detection task with composite objects as to-be-remembered items was intended to permit assessment of whether or not the mechanisms of (amodal) object completion require resources in VWM beyond those needed to represent objects that are not completed behind an occluder.

Experiment 1

Experiment 1 was performed to investigate the role of object completion in VWM, by assessing memory capacity for composite and simple objects, with the former giving rise to amodal completion. We employed a change detection paradigm (Luck & Vogel, 1997). Participants were randomly presented with a memory display of simple or composite objects for 300 ms, and after a brief delay, a probe item appeared (see Figure 2). The task was to decide whether the probe was the same or different relative to the object presented previously at the same location in the memory display. The presentation time of the memory display was set in accordance with previous studies (Sekuler et al., 1994), to ensure that completion could take place within the time allowed. If completion occurs and requires mnemonic resources, then performance was expected to differ for completed relative to uncompleted objects.

Method

Participants. 16 right-handed volunteers (9 female, 7 male) with normal or corrected-to-normal vision participated in Experiment 1. Their ages ranged from 18 to 30 years (M = 25.25 years, SD = 2.97 years). All participants were naive as to the purpose of the study. They participated in the experiment for payment of €8.00 per hour. All participants provided written informed consent, and the experimental procedure was approved by the ethics committee of the Department of Psychology, Ludwig-Maximilians-University, Munich.

Apparatus and Stimuli. The experiment was controlled by an IBM-PC compatible computer, running Matlab routines and Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997). The stimuli were black line drawings (0.2 cd/m^2) against a gray background (178 cd/m^2), presented on a 17-inch computer monitor (1024×768 pixel screen resolution, 85-Hz refresh rate). The experiment was conducted in a sound-attenuated room that was dimly lit.

The complete stimulus set is shown in Figure 1. The stimuli used in Experiment 1 were adapted from previous studies (Van Lier, Van der Helm, & Leeuwenberg, 1995; Plomp & Van Leeuwen, 2006); they are depicted in Figure 1A-D. As can be seen, they consisted of composite and simple objects. Each composite figure included a square with a second shape positioned partly occluded next to the square (Figure 1, Composite). The average amount of occlusion was 30% across all occlusion interpretations. Every simple figure was presented in three variants, corresponding to the three possible alternative interpretations of the composite object: global completion, local completion, and mosaic (Figure 1, Simple - Global, Local, Mosaic, respectively). Global completions presented a symmetrical shape interpretation of the occluded object, whereas a local completion was based on the linear continuation (interpolation) of the visible parts of the occluded shape. A mosaic figure simply presented a 2-D cut-out outline shape identical to the visible part of the partly occluded figure. The widest aspect of each simple object touched the borders of a circular region with a diameter of 2.4° of visual angle. The square of the occluded objects subtended 2.1° × 2.1° of visual angle. For each memory display, three distinct objects (from the same completion condition) were presented randomly at six positions within a circular region subtending 12.4° of visual angle.

Procedure and Design. Each trial started with the presentation of a central fixation cross for 500 ms. Next, participants were randomly presented with a memory display of simple or composite objects for 300 ms. Following a blank screen of 1000 ms, a simple figure probe (global, local, or mosaic) appeared at one of the locations that had previously been occupied by an item in the memory display. The probe display remained visible until participants responded. Participants responded with the left and, respectively, right mouse keys to indicate whether the probe object was the same as or different from the object at the same location in the previous, memory display. Note that “same” or “different” in this experiment refers to object identity, rather than to the completion type. For example, the occluded cross in Figure 1A (Composite) would be considered the same object in relation to all other simple objects that present a cross-shaped item (Figure 1A, Simple). The objects in a given memory display were randomly selected from the available set of stimuli, with the constraint that all objects were of the same completion type (i.e., global, local, or mosaic, respectively) and no object repeated in the same display. It should be noted that different completion types were presented in separate parts of the experiment, such that, for a given experimental part, all simple objects in the memory and probe displays would coherently support the same (global, local, or mosaic) object interpretation. Thus, blocking by completion type ensured that observers could generate a coherent interpretation in a consistent manner, potentially maximizing effects of amodal completion in the current experiment (see Albright & Stoner, 2002; Rauschenberger, Peterson, Mosca, & Bruno, 2004; Plomp & Van Leeuwen, 2006; Liu, Plomp, Van Leeuwen, & Ioannides, 2006; Plomp et al., 2006). Observers were asked to respond as accurately as possible; there was no stress on response speed. In case of an erroneous response, feedback was provided in the form of an 'alerting' sign ("–") presented for 1000 ms at the center of the screen. Trials were separated from each other by an interval of 1000 ms. Figure 2 illustrates typical examples of a trial sequence.

A within-subjects design was used. The independent variables were object configuration (simple or composite objects in the memory display), interpretation (global completion, local completion, or mosaic interpretation), and change in the probe display (yes, no). The experiment was subdivided into three parts, with each part displaying one type of possible interpretation. Thus, each part of the experiment presented only one type of (simple) object (i.e., global, local, or mosaic figure) in the memory and probe displays to enforce a corresponding interpretation of the composite (occluded) objects within a given experimental part (e.g. Albright & Stoner, 2002). The three parts were presented in random order. Within each part, the different configurations (simple, composite) and change and no-change trials were presented in randomized order across trials. There was one initial block of 12 practice trials, followed by 4 experimental blocks of 42 trials per part, yielding 504 experimental trials in total.

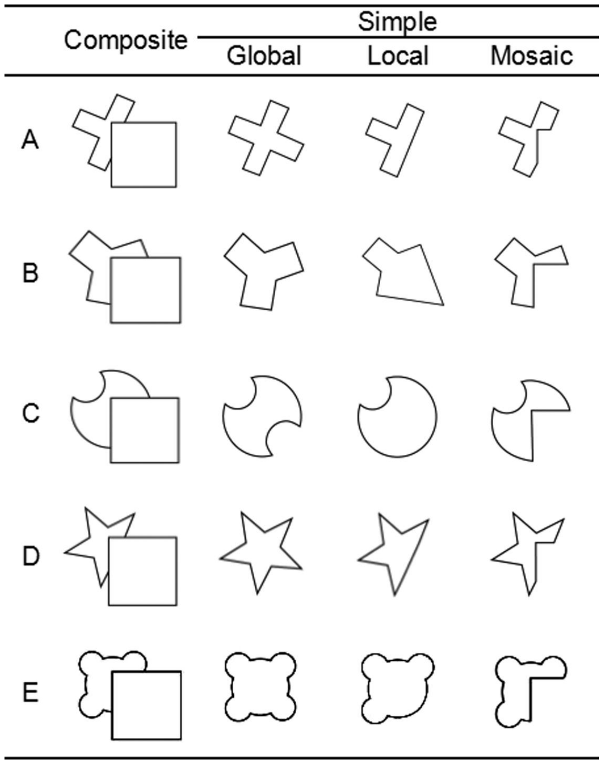

Figure 1. Illustration of experimental stimuli with their respective composite and simple versions (global, local completion, and mosaic interpretation), adapted from Van Lier et al. (1995), Plomp and Van Leeuwen (2006), and Sekuler et al. (1994).

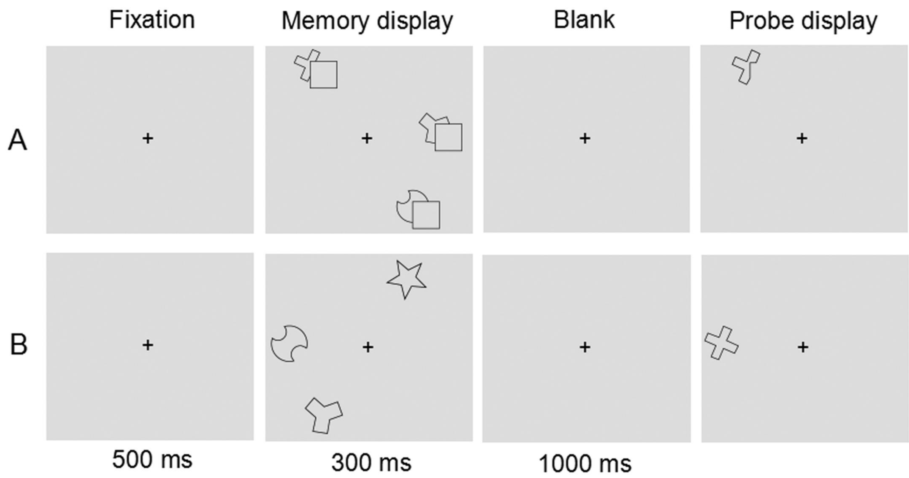

Figure 2. Experimental procedure. Panel A shows an example trial presenting a composite-object memory display followed by a probe supporting a mosaic interpretation. The correct response would be “same”. Panel B depicts an example trial with a simple-object memory display, presenting global completions. The correct response would be “different”.

Results

The primary dependent variable was *d'*, to examine participants' ability to distinguish change- from no-change trials regardless of any bias to respond “change” or “no change” within the Signal Detection Theory framework (Green & Swets, 1966)[1]. The sensitivity index *d'* is calculated as z (proportion hits) – z (proportion false alarms), with a hit defined as correct detection of a change and a false alarm as a “change” response in the absence of an actual change. Extreme, “perfect” scores were adjusted using the following formulas: $1 - 1/(2n)$ for hit rates of 100%, and $1/(2n)$ for zero false alarms, where n refers to the number of total hits or false alarms (Macmillan & Creelman, 1991).

Figure 3 presents the mean *d'* scores as a function of simple and composite object configurations in the memory display, separately for different interpretations. In addition, mean accuracy scores are provided in Table 1 (for all three experiments presented). A repeated-measures ANOVA on the *d'*

[1] Analyses of percent correct scores and capacity estimates *K* (Cowan, 2001) were also performed on all reported data. These analyses revealed identical patterns of results to that using *d'*, in all three experiments.

scores, with object configuration (simple, composite) and interpretation (global, local or mosaic) as within-participants factors, revealed a main effect of object configuration, F (1, 15) = 29.25, p < .0001, η_p^2 = .66, with higher sensitivity for simple (d' = 2.30) than for composite (d' = 1.90) objects, and a main effect of interpretation, F (2, 30) = 9.92, p < .0001, η_p^2 = .40, with higher sensitivity for global and local completion as compared to the mosaic interpretation (2.28, 2.25, and 1.76 for the global, local, and mosaic interpretations, respectively; all ps < .01). Importantly, there was also a significant interaction between object configuration and interpretation, F (2, 30) = 18.57, p < .0001, η_p^2 = .55, owing to the fact that sensitivity was highest for local, intermediate for global, and lowest for mosaic variants of simple objects (all ps < .05). By contrast, for composite objects, d' was higher for global as compared to both local and mosaic interpretations (all ps < .05).

Table 1. Mean Accuracies (proportion correct) in Experiments 1–3 for All Stimulus Conditions

Experiment	Set Size	Simple			Composite		
		Global	Local	Mosaic	Global	Local	Mosaic
1	3	0.86	0.88	0.79	0.83	0.79	0.78
2	3	0.82	0.85	0.77	0.76	0.78	0.77
3	2	0.93		0.89	0.90		0.86
	4	0.74		0.71	0.72		0.70

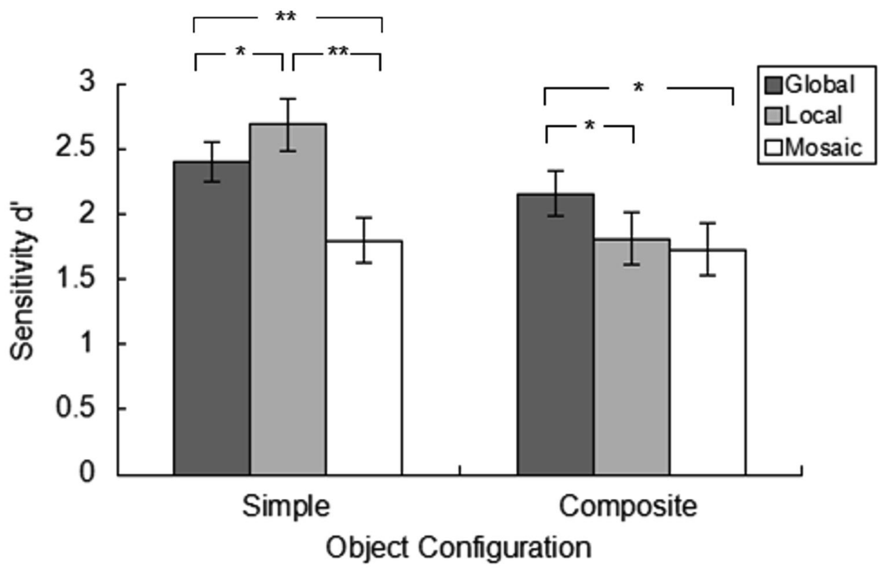

Figure 3. Mean change detection sensitivity, *d'*, as a function of the object configuration (simple, composite) in the memory display, separately for the different interpretations (global, local, mosaic) in Experiment 1. Error bars denote 95% (within-subject) confidence intervals. Significant differences revealed by pairwise comparisons are indicated by asterisks. * $p < .05$, ** $p < .001$.

Discussion

The results of Experiment 1 demonstrate that performance was overall lower for composite relative to simple objects. Moreover, the different variants of each stimulus also affected performance: Simple objects were associated with an increase in performance (i.e., in sensitivity) from mosaic through global to local objects. By contrast, for composite objects, the global completion interpretation exhibited the highest sensitivity score compared to the local completion and mosaic interpretations.

Note that, when comparing the various interpretations of composite with the corresponding simple objects, for the mosaic interpretation, sensitivity for the visible parts in composite (mosaic) objects was essentially equivalent to that with (physically identical) cutout segments in simple objects ($p = .52$) – indicating that the encoding of the (task-irrelevant) square occluder in composite objects did not affect task performance. By contrast, global and local completion interpretations were associated with reduced sensitivity for composite relative to simple objects (ps $< .05$) – presumably attributable to amodal completion, which requires additional VWM resources beyond the 'basic' representation of simple objects. It cannot be ruled out, though, that it also reflects differential shape discriminability amongst the to-be-remembered objects (see Awh, Barton & Vogel, 2007).

The effect of shape discriminability is most obvious when considering the pattern of results for simple objects: Mosaic shapes are the most complex ones of the set of stimuli presented, arguably making them difficult to represent and discriminate from each other, thus giving rise to the lowest change detection performance. Moreover, global shapes are presumably harder to memorize than local shapes, because global shapes are (by definition) more symmetric and overall less variable in their outline shapes, (see Figure 1), thus making it harder to maintain distinct representations of the presented objects. For instance, a local-object change (e.g., of the local "arrow" in Figure 1B into the local "T" shape in Figure 1A) might be more conspicuous than the very same change for the global set of objects (e.g., of the global "cross" in Figure 1A into the global "wind wheel" in Figure 1B), simply because the local changes on average involve a larger change in the size of the object compared to global changes. In this view, the differences in performance among the various simple objects can be taken to reflect the ease with which a given shape can be discriminated from other to-be-remembered shapes.

Direct evidence of amodal completion in VWM is revealed when comparing the various interpretations of the composite objects: the depicted shapes (for the various interpretations) are all physically identical and therefore are equally difficult to discriminate from each other. Despite identical shapes for each of the possible composite object interpretations, sensitivity was nevertheless substantially higher for global completions compared to all other object types sensitivity – indicating that observers were more sensitive to detect a change when a given shape could be amodally completed to form a global object, as compared to an identical, uncompleted mosaic shape. At the same time, however, the amodally completed shape required more VWM capacity than a comparable simple global shape that does not require to be completed behind the occluding square ($p < .05$, see above). In contrast, no benefit of amodal completion was evident when comparing composite local with composite mosaic objects. This pattern of results is essentially in line with findings from other approaches studying amodal completion in purely visual tasks without the specific engagement of

VWM resources (e.g. Sekuler, 1994; Sekuler et al., 1994; Van Lier, 1999, 2001; Van Lier & Wagemans, 1999; De Wit & Van Lier, 2002). Taken together, these studies suggest that global completion is the default, or preferred, mode of interpretation by which partly occluded objects are completed. Thus, both perceptual analysis and mnemonic processing are governed by a tendency to maximize the symmetry of an occluded object (in the global completion interpretation), while completion on the basis of good continuity (in the local completion interpretation) is less likely to be employed.

It should be noted that our experiment presented simple and composite object displays blocked by object interpretation, that is, with separate experimental parts for global, local, and mosaic interpretations, respectively. Thus, in each part, the presented simple object shapes may have primed the processing of composite objects, and in fact it has been shown that the type of occlusion depends on the presented context (Rauschenberger et al., 2004; Plomp & Van Leeuwen, 2006; Plomp et al., 2006; Liu et al., 2006; Peterson & Hochberg, 1983). Thus, contextual information (i.e., the prevailing interpretation as afforded by the simple objects in a given part of the experiment) may be used to guide the encoding of the composite objects in VWM. In other words, the context provided by simple objects throughout a given part of the experiment might be regarded as 'priming' an interpretation of the presented composite objects (Plomp & Van Leeuwen, 2006). As described above, such priming by the simple object context was particularly effective for global completions, while there was no comparable priming of local completions. – Next, in Experiment 2, we set out to examine whether a global completion benefit in VWM would be replicable without an influence of context.

Experiment 2

Experiment 1 revealed evidence for an effect of global object completion in VWM. Importantly, in Experiment 1, the different – global, local, and mosaic – interpretations as given by the simple objects in the memory and probe displays were presented in separate parts of the experiment. Accordingly, these simple objects provided some kind of consistent context within which the composite objects were interpreted. In Experiment 2, we investigated whether evidence for object completion in VWM would also be obtained in the absence of such a consistent context favoring a given interpretation throughout a block of trials. To this end, memory displays with simple and, respectively, composite objects were presented separately in different blocks (and interpretations, for composite objects now enforced only by the probe display, were presented in randomized order). That is, simple memory display objects were no longer available to support a consistent interpretation of the composite objects. If the interpretation of a given composite object is determined mainly by the context prevailing throughout a block of trials (as was the case in Experiment 1), then we would expect that, without such a consistent context, change detection for composite objects is comparable across the global, local, and mosaic interpretations.

Method

Experiment 2 was largely identical to Experiment 1, with the following exceptions. We tested a new group of 16 right-handed paid volunteers (10 female, 6 male; mean age = 23.8 years; normal or corrected-to-normal vision). Simple and composite memory display objects were presented in different experimental blocks, whereas the different interpretations (which, for composite objects, were provided solely by the single simple object shown in the probe display) and change and no-change trials were presented in random order within each block. The experiment started with two blocks of 12 practice trials (presenting either simple or composite memory displays), followed by 20 experimental blocks of 24 trials each, amounting to 480 experimental trials in total. Participants were presented with the simple and composite blocks in randomized order.

Results

A repeated-measures ANOVA with main terms for object configuration (simple, composite) and interpretation (global, local, or mosaic) revealed both main effects to be significant: object configuration, F (1, 15) = 6.32, p < .05, η_p^2 = .30; and interpretation, F (2, 30) = 9.76, p < .001, η_p^2 = .39. Sensitivity was significantly higher for simple (d' = 1.92) than for composite (d' = 1.62) objects, and higher for local than for global and mosaic interpretations (d' = 1.96, 1.73, and 1.62, respectively; all ps < .05). The interaction between object configuration and interpretation was also significant, F (2, 30) = 5.33, p < .01, η_p^2 = .26, but it showed a different pattern to that in Experiment 1. As can be seen in Figure 4, for simple objects, sensitivity increased from the mosaic through the global to the local interpretation (all ps < .05) – a near-identical pattern to that obtained in Experiment 1. For composite objects, by contrast, there were no significant differences among all three possible interpretations (all ps > .5).

Further analyses were conducted to compare the simple and composite object conditions in Experiments 1 and 2. First, an analysis of the simple objects revealed a main effect of interpretation, F (2, 60) = 35.60, p < .0001, η_p^2 = .54, with the highest sensitivity for local and the lowest sensitivity for mosaic figures (all ps < .001), without a significant difference between experiments (p = .089) and without a corresponding interaction (p = .19). This suggests that VWM for simple objects was overall comparable across the two experiments. Second, for the composite objects, there was a significant interaction between experiment and interpretation, F (2, 60) = 3.58, p < .05, η_p^2 = .11. In Experiment 1, there was a significant advantage for detecting a change for the global interpretation of composite objects, while no comparable effect was evident in Experiment 2. There were no differences in detecting the change for the local and mosaic interpretations in Experiments 1 and 2 (all ps > .59).

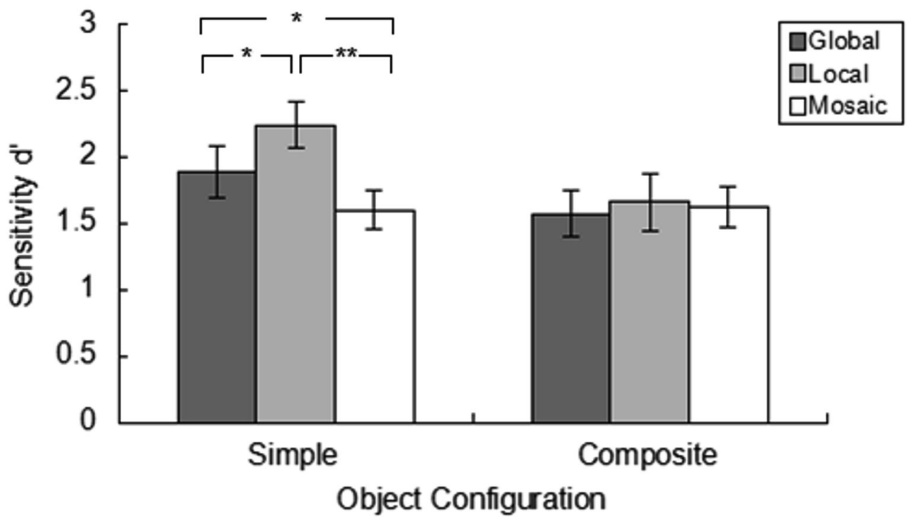

Figure 4. Mean change detection sensitivity, *d'*, as a function of the object configuration (simple, composite) in the memory display, separately for different interpretations (global, local, mosaic) in Experiment 2. Error bars denote 95% (within-subject) confidence intervals. Significant differences revealed by pairwise comparisons are indicated by asterisks. * $p < .05$, ** $p < .001$.

Discussion

The results of Experiment 2 directly replicated the pattern of results for simple objects in Experiment 1, but revealed no evidence of object completion for composite figures. In fact, both global and local completion interpretations for composite objects yielded a level of performance that was the same (i.e., as low) as that for the mosaic baseline – suggesting that without the 'priming' provided by the simple-object context, no particular grouping emerges. The combined results of Experiments 1 and 2 thus support previous findings showing that a given context can determine how composite objects are interpreted (see also Rauschenberger et al., 2004; Plomp & Van Leeuwen, 2006; Liu et al., 2006; Plomp et al., 2006). In fact, object representations in VWM may be constructed based on context-activated top-down knowledge. This knowledge frames how objects are represented, in turn determining processes of object recognition and the change/no-change decisions to be made in the present task (Bar, 2003; see also Conci & Müller, 2014). Thus, the actual completion representation derived from the visual input is constrained by the context within which an occluded object is presented.

Experiment 3

The two experiments reported thus far demonstrate that, when presented within an appropriate context, objects are stored as (globally) completed representations in VWM, where the storage or maintenance of completed wholes draws on limited-capacity VWM resources. If this 'resource' notion is correct, then varying the set size of the memory display such that it either stays within (2 items) or exceeds (say 4 items) the available capacity for representing objects should have an influence on object completion in VWM. This idea was tested in Experiment 3.

Method

Experiment 3 was basically identical to Experiment 1, with the following differences. 16 right-handed paid volunteers (8 female, 8 male; mean age = 24.25 years; normal or corrected-to-normal vision) participated in the experiment. The memory display presented two possible set sizes: two or four objects. The stimulus set was based on five different shapes (adapted from Van Lier et al., 1995; Plomp & Van Leeuwen, 2006; Sekuler et al., 1994; see Experiment 1, Figure 1A–E) and consisted of composite and simple objects. As Experiment 1 had shown that global completion leads to superior VWM performance relative to local completion, in Experiment 3, only global completions were presented and compared to (baseline) mosaic interpretations. Thus, every simple figure could be one of two possible interpretations: global completion and mosaic (see Figure 1). A within-subjects design was used. The independent variables were set size (2, 4), object configuration (simple, composite), interpretation (global, mosaic), and change (yes, no). The experiment was subdivided into two parts, with each part inducing one possible interpretation (global or mosaic interpretation), comparable to the procedure in Experiment 1. Participants were presented with the global and mosaic interpretation (experimental) parts in counterbalanced order (i.e., one half starting with the global and the other with the mosaic part). Within each part, different set sizes, object configurations, and change and no-change trials were presented in random order. There was one block with 16 practice trials and 7 experimental blocks of 48 trials in each part, yielding 672 experimental trials in total.

Results

Figure 5 displays the sensitivity *d'* as a function of set size, separately for different object configurations and interpretations. A repeated-measures ANOVA with main terms for set size, object configuration, and interpretation revealed the main effects of set size, F (1, 15) = 506.11, $p < .0001$, $\eta_p^2 = .97$, object configuration, F (1, 15) = 13.78, $p < .01$, $\eta_p^2 = .48$, and interpretation, F (1, 15) = 27.75, $p < .0001$, $\eta_p^2 = .65$, to be significant. Sensitivity was higher for set size 2 ($d' = 2.79$) than for set size 4 ($d' = 1.25$), higher for simple ($d' = 2.12$) than for composite ($d' = 1.91$) objects, and higher for global completion ($d' = 2.17$) than for mosaic interpretations ($d' = 1.86$). Most importantly, the interaction between set size and interpretation was significant, F (1, 15) = 12.65, $p < .01$, $\eta_p^2 = .46$: as the set size increased from 2 to 4 objects, the difference between global completion and mosaic interpretations decreased (mean difference: .49, $p < .0001$, and .14, $p < .05$, for set sizes 2 and 4, respectively).

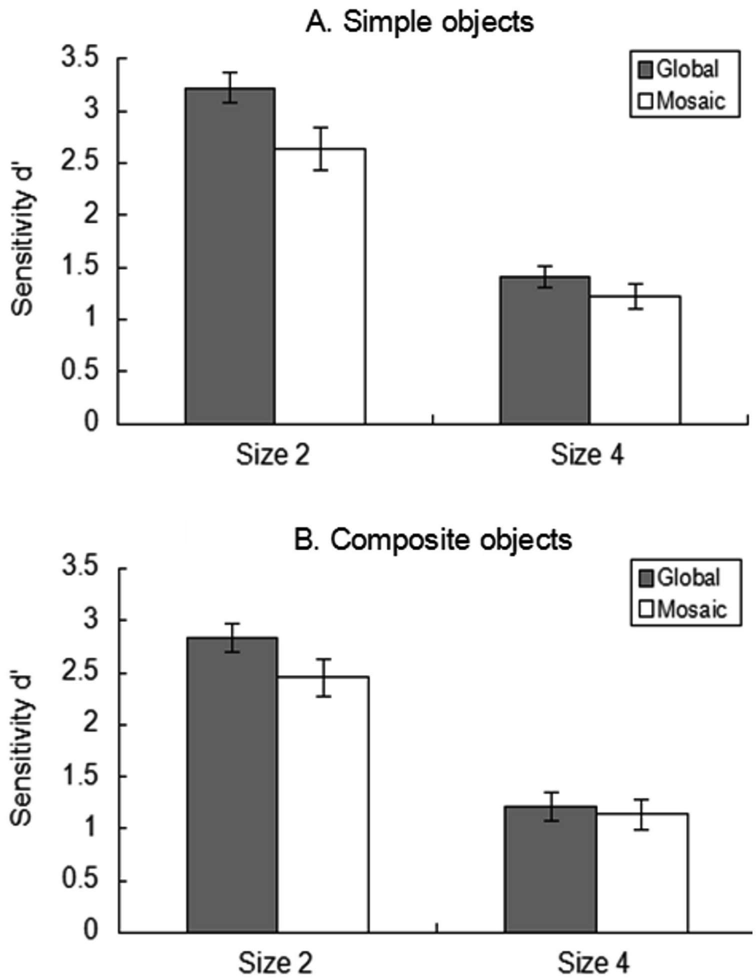

Figure 5. Mean change detection sensitivity, *d'*, as a function of memory display set size, separately for different interpretations (global, mosaic) and object configurations (A. simple objects; B. composite objects) in Experiment 3. Error bars denote 95% (within-subject) confidence intervals.

Discussion

Experiment 3 was performed to examine how object completion in VWM is affected by memory capacity, as tested by means of a set size manipulation. The results replicated the findings from Experiment 1, with higher performance for the global completion than for the mosaic interpretation for both simple and composite objects. Note that completion also interacted with set size: the benefit for global (relative to mosaic) configurations largely decreased when set size increased from 2 to 4 items. This pattern is consistent with the idea that, with an increase in the number of to-be-memorized objects, there is an increase in storage demands; as a result, less processing resources are available for each individual object, leading to a decline of change detection performance overall. However, in addition to this overall decline, the performance difference between global and mosaic configurations is reduced, which may be taken to indicate that completion occurs only when sufficient mnemonic resources are available.

General Discussion

The present study investigated VWM for composite objects using a change detection paradigm and measuring performance in terms of (change detection) sensitivity *d'*, that is, how well a participant was able to distinguish between trials on which the probe changed as compared to staying the same. The results from three experiments consistently showed that participants performed overall better with simple than with composite objects. Moreover, Experiment 1 revealed better performance for global completion as compared to local completion and mosaic interpretations. This global completion advantage was obtained only when the simple-object context supported a global object interpretation of the amodal stimuli. By contrast, without an appropriate context (in Experiment 2), no such benefit for global completions was found. Experiment 3 further showed that, even with an appropriate context, the difference between global completion and mosaic interpretations reduced as the memory display set size increased to (or beyond) the maximum of VWM capacity.

Taken together, these results indicate that amodal completion occurs for objects represented in VWM and this completion process is significantly affected by the context of simple objects (presented together with the amodal stimuli): completion occurs only when the context supports a given interpretation of the completed object. Without corresponding context, change detection for the various kinds of composite objects is comparable, with sensitivity measures for global (and local) completion types being similar to VWM performance with mosaic configurations. Previous studies have already shown that context affects how a given composite object is perceived (Rauschenberger et al., 2004; Plomp & Van Leeuwen, 2006; Plomp et al., 2006; Liu et al., 2006). While our results are in line with these findings, they extend them by showing that the influence of context on processes of amodal completion continues from basic perceptual analysis to subsequent stages related to the short-term retention of the presented stimuli in VWM. This influence of object completion on VWM may be due to a top-down facilitation mechanism as demonstrated by Bar (2003). On this view, recognition of a visual image would activate concurrent expectations about likely interpretations associated with the specific image. Via such top-down expectancies, contextual knowledge or prior expectations might influence the interpretation of an object in VWM (see also Conci & Müller, 2014). Thus, for our paradigm, a consistent context would activate a specific interpretation of a given composite object, consequently biasing the completion type that determines a given VWM representation.

Our results reveal that composite objects tend to be represented as globally completed wholes in VWM, suggesting that memory-related processing is determined preferentially by global object structure – in line with several previous studies that found global (but not local) completion was the dominant interpretation of an occluded object (Sekuler, 1994; Sekuler et al., 1994; Van Lier, 1999, 2001; Van Lier & Wagemans, 1999; De Wit & Van Lier, 2002). There is some evidence suggesting that initial stimulus processing may represent occluded objects in terms of a mosaic interpretation (e.g., in a visual search task, see Rauschenberger & Yantis, 2001; Plomp et al., 2006). However, as processing time increases, this interpretation is superseded by complete-object representations (Plomp & Van Leeuwen, 2006; Plomp et al., 2006).

A second influence on completion processes in memory is the limited capacity of VWM itself.

Experiments 1 and 3 used comparable experimental manipulations, presenting a consistent stimulus context to facilitate (global) completion. In Experiment 1, detection of the change was somewhat more difficult for globally completed composite as compared to simple objects. By contrast, performance with mosaic configurations was comparable for composite and simple objects (while being overall reduced relative to performance for composite and simple global objects). This pattern of results indicates that the storage of a completed whole requires additional mnemonic resources, over and above those required for the representation of the very same unoccluded object. That is, the demands associated with completion directly impact memory capacity: a complete-object representation in VWM affects storage in that it occupies more capacity. This is consistent with previous visual search studies showing that search efficiency is reduced for complete-object representations relative to comparable uncompleted objects (He & Nakayama, 1992; Rensink & Enns, 1998; Davis & Driver, 1998).

On the other hand, although the composite objects were more likely to be represented in VWM as completed wholes compared to other interpretations, when there was a concurrent increase in storage demands (i.e., when the memory display set size increased in Experiment 3), the advantage for the global completion condition greatly reduced. As suggested by Alvarez and Cavanagh (2004), the number of items stored in VWM depends on the visual information load of the individual items. Processing of completed objects presumably poses higher demands on the available (limited) resources. When the number of the composite objects exceeds the available VWM capacity, it appears that completed objects are simply represented in terms of their corresponding visible fragments (i.e., in terms of a mosaic interpretation), thus consuming fewer resources.

In this view, the maintenance of the completed wholes is not only, or simply, influenced by the number of objects, but also limited by completion processes, which requires resources. This is in line with Alvarez and Cavanagh's (2008) suggestion that VWM may involve two dissociable stages: In the first stage, low-resolution "boundary features" are extracted by means of parallel perceptual processing, whereas in the second stage, more detailed, high-resolution features are extracted via serial, attentive perceptual processing. Thus, different representations of the same composite stimuli stored in VWM may be extracted at different stages of perceptual processing. Once the completed representations are available, they are represented preferentially as global wholes compared to other interpretations – at least as long as enough resources are available.

Implications for limitation of VWM capacity

In the present study, VWM capacity for simple or composite objects was limited to about 2 items, as indicated by estimations of the capacity estimate *K* (see Table 2). Thus, compared to Luck and Vogel (1997), who report a *K* value of about 4 objects, our rather complex shape stimuli yielded a relatively low capacity estimate. Nevertheless, our estimates are in accordance with other studies that presented relatively complex items, such as Snodgrass line drawings or random polygons (see Alvarez & Cavanagh, 2004). According to our current results, completion resulted in reduced change detection performance and was more likely to be compromised as the number of stored items increased. This presumably indicates that VWM can represent visual information until some maximum is reached, but the number of items represented is crucially determined by completion and complexity. This is consistent with the notion of VWM as a system with a storage capacity that varies as function of object complexity (Alvarez & Cavanagh, 2004; Xu, 2002). Interpreted within this perspective, our results would indicate that the encoding of items into VWM draws on a more continuous resource, instead of involving an all-or-none (e.g., slot-like) storage process, arguing against the view that VWM represents a fixed number of items regardless of complexity (Luck & Vogel, 1997; Awh et al., 2007; Rouder et al., 2008).

Table 2. Capacity Estimates *K*

Experiment	Set size	Simple	Composite
1	3	2.06	1.79
2	3	1.87	1.62
3	2	1.63	1.56
	4	1.83	1.65

Previous formal models of change detection to estimate VWM capacity assume that observers encode only a simple memory representation that includes no higher-order information (e.g., Luck & Vogel, 1997; Zhang & Luck, 2008). However, real-world scenes are typically complex and present structure that provides higher-order constraints on to-be-remembered items (for a review, see Brady, Konkle, & Alvarez, 2011; Brady & Tenenbaum, 2013; Conci & Müller, 2014). Our study supports the view that contextual information and prior knowledge are utilized to perform working memory tasks. The same composite objects were represented differently depending on the contextual information, and each representation requires varying amounts of mnemonic resources. Moreover, while existing formal models of VWM treat all items independently of each other (e.g., Luck & Vogel, 1997; Zhang & Luck, 2008), the present findings suggest that VWM encodes grouped items. In light of the current results, approaches taking higher-order (context) information and relational structures between items into consideration might be better suited to account for human change detection performance.

Conclusion

Previous studies have shown that completed objects are processed rather efficiently, in sequential perceptual (mosaic and completion) stages. Our findings indicate that at a later, post-perceptual stage, the maintenance of composite object representations in VWM is influenced by contextual information and VWM capacity limits. Composite objects are preferentially stored as globally completed wholes when primed by concurrent simple global objects, but completion only occurs with sufficient available mnemonic resources. These findings support the view of VWM as reflecting a continuous resource, where capacity limitations depend on the structured representation of to-be-remembered objects.

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