Object maintenance beyond their visible parts in working memory

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Abstract

Completion of a partially occluded object requires that a representation of the whole is constructed based on the information provided by the physically specified parts of the stimulus. Such processes of amodal completion rely on the generation and maintenance of a mental image that renders the completed object in visual working memory (VWM). The present study examined this relationship between VWM storage and processes of object completion. We recorded event-related potentials to track VWM maintenance by means of the contralateral delay activity (CDA) during a change detection task in which to-be-memorized composite objects (notched shapes abutting an occluding shape) were primed to induce either a globally completed object or a non-completed, mosaic representation. The results revealed an effect of completion in VWM despite physically identical visual input: Change detection was more accurate for completed as compared to mosaic representations when observers were required to memorize two objects, and these differences were reduced with four memorized items. At the electrophysiological level, globally completed (versus mosaic) objects gave rise to a corresponding increase in CDA amplitudes. These results indicate that, while incorporating the occluded portions of the presented shapes requires mnemonic resources, the complete-object representations thus formed in VWM improve change detection performance by providing a more simple, regular shape. Overall, these findings demonstrate that mechanisms of object completion modulate VWM, with the memory load being determined by the structured representations of the memorized stimuli.

Keywords: visual working memory, amodal completion, contralateral delay activity

New & Noteworthy

This study shows that completion of partially occluded objects requires visual working memory (VWM) resources. In the experiment reported, we induced observers to memorize a given visual input either as completed or as non-completed objects. The results revealed both a behavioral performance advantage for completed vs. non-completed objects despite physically identical input, and an associated modulation of an electrophysiological component that reflects VWM object retention – thus indicating that constructing an integrated object consumes mnemonic resources.

Introduction

Amodal completion refers to the phenomenon that occluded parts of an object are perceptually ‘filled in’ (Michotte, Thines, & Crabbe, 1964/1991), that is, missing information is (re-) constructed based on the partial physical stimulation available (see Figure 1, composite, for example stimuli). Representing amodally completed objects has been suggested to rely on mental imagery (Nanay, 2010). While completion is largely dependent on the structural properties of a given stimulus (van Lier, van der Helm, & Leeuwenberg, 1994), it may additionally be influenced by background information, such as semantic knowledge about a given object or the context within which it is presented – providing further information about what the occluded parts of an object (may) look like (Hazenberg & van Lier, 2016; Rauschenberger, Peterson, Mosca, & Bruno, 2004). Construction of a mental image typically engages visual working memory (VWM) resources (Baddeley & Andrade, 2000). On this view, rather than just subserving passive maintenance of visual information for short periods of time, VWM does also involve active processes of generating (hidden) parts of objects in memory. The current study was designed to investigate such active object completion processes in VWM, that is, to elucidate how physically specified parts of a stimulus are combined with completed fragments to generate a coherent, whole-object representation.

A common and widely used paradigm for studying VWM is change detection (Luck & Vogel, 1997). In this paradigm, participants are asked to remember a set of objects in an initial memory display. After a retention interval, a test display is presented and participants have to indicate whether a change has occurred in one of the objects in the test as compared to the memory array. The typical finding is that some three to four objects can be maintained concurrently in VWM (Luck & Vogel, 1997; Cowan, 2001). However, the number of items that can be stored has also been shown to be influenced by the information load associated with the individual, to-be-memorized objects. For instance, Alvarez and Cavanagh (2004) demonstrated that change detection performance varies as a function of stimulus complexity, with a reduced number of only about one memorized item for more complex objects (e.g., Chinese characters, shaded cubes), as compared to four items for more simple objects (e.g., colored squares). Thus, VWM is limited in capacity: it can represent only relatively few items, where the overall number of items that can be retained varies for different types of objects.

Studies that examined participants' electroencephalogram (EEG) in change detection tasks showed that an event-related difference wave manifesting during the delay period (between the memory and test displays) over lateral posterior parietal and occipital electrode sites – referred to as 'contralateral delay activity' (CDA) – can serve as an online marker of current VWM load: the CDA amplitude increases with the number of items (to be) held in memory, until reaching an asymptotic limit indicative of an individual's memory capacity (Vogel & Machizawa, 2004). Given that the CDA (which is obtained in the delay period) reflects processes of maintenance (independent of later processes involved in the comparison of the memorized items with the test probe; see Awh, Barton, & Vogel, 2007), it can be used to directly examine how stimuli are represented in VWM. For instance, with relatively few to-be-memorized items, CDA amplitudes were found to be larger for more complex (random polygons) than for simple objects (colored squares) – in line with the view that VWM is modulated by stimulus attributes and the load they place on processes of maintenance (Luria, Sessa, Gotler, Jolicœur, & Dell'Acqua, 2010; Gao et al., 2009; Töllner, Conci, Rusch, & Müller, 2013). Moreover, larger CDA amplitudes were observed for identical stimuli when the task required the encoding of objects with high precision (Machizawa, Goh, & Driver, 2012). This demonstrates that identical visual input may change the memory load depending on top-down demands (see also Balaban & Luria, 2016). Nevertheless, it remains an open issue whether the CDA varies with the extent to which processes of completion modify a given object in VWM.

The question at issue here, namely: the role of object completion in VWM, was recently examined in a behavioral study employing the change detection paradigm (Chen, Müller, & Conci, 2016). Chen et al. presented memory displays that were physically identical, but varied the structural information of the objects' representations in memory by introducing additional, contextual information. The memory displays participants were presented with were essentially comparable to the example displays depicted in Figure 2 (except that, in Chen et al., 2016, participants were not pre-cued to the task-relevant side of the display by an arrow symbol). A given memory display consisted either of composite objects (i.e., presenting a notched figure adjacent to a square) or of simple objects (i.e., comparable shapes but without the adjacent square). Importantly, the simple object could be one of several possible interpretations of the notched figure, with a global, symmetrical shape that provides a completed interpretation of the composite object (Figure 1, global), or a so-called 'mosaic' figure (Figure 1, mosaic), where mosaic simply refers to a 2-D cut-out outline shape identical to the visible part of the figure (Sekuler & Palmer, 1992). Presentation of the memory display was followed by a brief delay, after which a (simple-object) test probe appeared. The task was to decide whether this probe was the same as or different from the corresponding item in the memory display. Each block of trials presented only one type of (simple) objects (either global or mosaic figures), to enforce, or 'prime', a consistent interpretation of the composite objects within the given block. The results revealed global objects to yield higher change detection accuracy, indicative of an advantage in retaining completed wholes over partial shapes (Chen et al., 2016, Experiment 1). This advantage for completed, relative to mosaic, *composite* objects disappeared when global and mosaic *simple* object displays were presented randomly intermixed within trial blocks (Chen et al., 2016, Experiment 2), indicating that the effect of completion is determined by some top-down set provided by a consistent context of the available simple object interpretations.

Importantly, Chen et al. (2016) compared change detection accuracy for physically identical composite objects that participants were made to interpret either as completed wholes or as non-completed mosaic objects. Consequently, rather than being attributable to an influence of perceptual shape discriminability, the performance advantage for global (relative to mosaic) composite objects obtained by Chen et al. (2016, Experiment 1) can only be attributed to the additional completion process, which renders binding of the physical parts of the object with the occluding parts of the surface. If VWM load is indeed modulated by the completion of the memorized objects, this would predict that the alternative representations of the composite object would manifest in a modulation of the CDA amplitude. On this view, the CDA amplitude not only reflects the passive retention of items, but also the resource demands associated with processes required for integrating fragments into a coherent, whole-object representation. This viewpoint contrasts with a more passive conception of

VWM, where the CDA would only be related to the basic storage of individuated items without any concurrent processing of the retained stimulus material.

The present study was designed to decide between these two alternative views and to extend our previous, purely behavioral findings regarding the relationship between VWM storage and the completion of objects (Chen et al., 2016). To this end, we combined behavioral measures with analysis of the CDA as an electrophysiological marker of VWM load. Event-related potentials (ERPs) were recorded from young adults while they performed a change detection task. On each trial (Figure 2), observers were first presented with an arrow cue indicating the relevant, to-be-memorized half of the display. Next, a brief bilateral array presented composite or simple objects (either global or mosaic shape interpretations; see Figure 1) for 300 ms. The (300-ms) presentation time of the memory display was set in accordance with previous studies (Sekuler & Palmer, 1992; Rauschenberger et al., 2004; Chen et al., 2016; Gerbino & Salmaso, 1987), which showed that completion only occurs when a given partially occluded stimulus is presented for at least 100–200 ms. Moreover, we provided a consistent context of simple-object trials within a given block, so as to effectively enforce a given interpretation of the partially occluded objects (Rauschenberger et al., 2004; Chen et al., 2016). Participants' task was to remember the items in the cued hemifield and indicate, after a brief delay, whether a subsequently presented test display did or did not contain a changed object. If completion modulates VWM load, the identical composite objects should yield a difference in performance for globally completed versus mosaic interpretations.

Method

Participants

Seventeen right-handed volunteers (8 males), with normal or corrected-to-normal vision (*M* = 24.22 years, *SD* = 2.90 years), took part in this study for payment of € 8.00 per hour. All participants provided written informed consent. The experimental procedures were approved by the local ethics committee (Department of Psychology, Ludwig-Maximilians-Universität München). Sample size was determined on the basis of previous, comparable studies (e.g., Luria et al., 2010), aiming for 85% power to detect an effect size of 0.8 with an alpha level of .05.

Apparatus and Stimuli

Stimuli were black line drawings (0.2 cd/m^2) presented against a light gray background (178 cd/m^2) on a 19-inch computer monitor (1024×768 pixel screen resolution, 85-Hz refresh rate). The stimulus set was based on six different shapes (adapted from van Lier et al., 1995; Plomp & van Leeuwen, 2006; Sekuler, Palmer, & Flynn, 1994; see Figure 1). The composite figure included a square with a second shape positioned partly occluded next to the square (Figure 1, Composite). The simple figure was presented in two possible alternative interpretations of the composite object: global and mosaic (Figure 1, Simple-Global, Simple-Mosaic). Global figures presented a globally completed, symmetrical shape, whereas a mosaic figure simply presented a 2-D cutout outline shape identical to the visible part of the partly occluded figure. At a viewing distance of 60 cm, each simple figure touched a circular region with a radius of 0.6° of visual angle. The square of the occluded objects subtended 1.1° x 1.1°. For each memory display, four or eight distinct objects of the same completion type were presented randomly at ten positions within a circular region with a radius of 5.0°, with two or four objects in each hemifield. A given shape could appear only twice at most in the same display. The test probe was identical to the item in the same position of the memory display in half the trials and different in the other half. It should be noted 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 as the other two variants of simple objects presenting a cross-shaped item (Figure 1a, Simple).

Procedure and Design

Each trial started with the presentation of a central fixation cross for 500 ms, followed by an arrow cue pointing to either the left or the right for 500 ms. Next, participants were presented with a memory display of either simple or composite objects for 300 ms. Following a blank screen of 900 ms, the test display was presented until a response was issued. Participants were instructed to memorize the stimuli presented in the hemifield indicated by the arrow cue and respond with left and right mouse keys to indicate whether the test probe in the cued hemifield was the same as or different from the corresponding item in the memory display. Left/right responses were counterbalanced across observers to control for stimulus-response compatibility effects. Observers were asked to respond as accurately as possible, without stress on response speed. Trials were separated from each other by a random interval between 300 and 400 ms. Figure 2 illustrates typical examples of a trial sequence.

There were eight experimental blocks, with 160 trials each. Each block presented only one type of possible interpretations (global or mosaic) to consistently enforce the respective interpretation of the composite objects within a given experimental block (Chen et al., 2016). The eight blocks were presented in random order. Within each block, the different configurations (simple, composite) and change/no-change trials were presented in randomized order across trials. All participants performed eight practice blocks of 40 trials each on the day before the experiment, to become familiar with the task.

Figure 1 about here

Figure 2 about here

EEG Recording and Data Analysis

The EEG was continuously recorded using 64 Ag/AgCl active electrodes (Brain Products Munich) according to the international 10-10 System with a sampling rate of 1000 Hz. Vertical and horizontal eye movements were monitored with electrodes placed at the outer canthi of the eyes, and respectively, the superior and inferior orbits. The electrode signals were amplified using BrainAmp amplifiers (BrainProducts, Munich) with a 0.1 – 250-Hz bandpass filter. All electrode impedances were kept below 5 kΩ. During data acquisition, all electrodes were referenced to FCz, and re-referenced off-line to averaged mastoids. Prior to segmenting the EEG, the raw data was visually inspected in order to manually remove nonstereotypical noise. Next, an infomax-independent component analysis was run to identify components representing blinks and horizontal eye movements, and to remove these artifacts before backprojection of the residual components. Subsequently, the data were band-pass filtered using a 0.1 – 40-Hz Butterworth IIR filter (24 dB/Oct). Signals were then averaged off-line over a 1200-ms epoch relative to a 200-ms pre-stimulus (memory display) baseline. Trials with artifacts –defined as any signal exceeding ± 60 μV, bursts of electromyographic activity (as defined by voltage steps/sampling point larger than 50 μV) and activity lower than 0.5 μV within intervals of 500 ms (indicating bad channels) – were excluded from averaging. The contralateral delay activity (CDA) was measured at parieto-occipital electrodes (PO7/8) as the difference in mean amplitude between the ipsilateral and contralateral waveforms relative to the memorized display, with a measurement window of 500–1200 ms after the onset of the memory display. Trials with incorrect behavioral responses were discarded from the ERP analyses.

Differences in behavioral accuracy and neural measures (CDA amplitudes) were examined for composite objects by performing two-way repeated-measures analyses of variance (ANOVAs) with the factors set size (two, four) and interpretation (global, mosaic). Note that the focus of the analysis on the maintenance of identical composite objects with varying interpretations (global vs. mosaic) controls for the influence of differential (perceptual) feature discriminability between the memory displays. Thus, any difference in the CDA components between global and mosaic representations can only be due to their differential maintenance demands, rather than to perceptual dissimilarity or memory–test comparisons. In addition to this main analysis of composite objects, we performed analogous analyses for simple objects.

Results

Composite Objects

Behavioral Data. Figure 3a depicts the mean percentage of correct responses for composite objects as a function of set size, separately for the different interpretations. A repeated-measures ANOVA on the accuracy data was performed with the factors set size and interpretation, yielding main effects of set size, $F(1, 16) = 767.07$, $p < .0001$, $\eta_p^2 = .980$, and interpretation, $F(1, 16) = 39.06$, $p < .0001$, $\eta_p^2 = .709$. Accuracy was higher for set size 2 (84%) than for set size 4 (67%), and higher for global (77%) than for mosaic interpretations (74%). The interaction between set size and interpretation was also significant, $F(1, 16) = 11.62$, $p = .004$, $\eta_p^2 = .421$: a significant difference between global (86%) and mosaic interpretations (81%) manifested with set size 2, $t(16) = 6.66$, $p < .0001$, while this difference was reduced for set size 4 (global: 68%; mosaic: 67%), $t(16) = 1.88$, $p = .078$. Replicating our previous findings (Chen et al., 2016), this reduction in performance can be attributed to the reduced scanning time available per object with an increased set size. As a result, not all objects are effectively completed for the larger, 4-item display. With larger memory arrays, there would then also be a higher chance of guessing, as attention is less likely focused on the object that is tested later on – so that this item might not have been encoded with sufficient detail. Moreover, accuracy might also be compromised by errors arising from the comparison of an item held in memory with the test probe presented (Awh et al., 2007), and these comparison errors might also increase with set size.

In a next step, we computed Cowan's *K* (Cowan, 2001), an estimate of visual memory capacity, which allows correcting for errors that result from memory storage failures. Note, however, that K does not take care of errors arising from the comparison process – which is why K might somewhat underestimate the number of items stored (though this underestimation should be comparable for global and mosaic interpretations). Essentially, this correction assumes that if an observer can hold *K* items in memory from an array of *S* items, the item that changed should be one of the items being held in memory on *K/S* trials, resulting in correct performance on *K/S* of the trials on which an item changed. *K* is computed according to the formula: (Proportion Hits – Proportion False Alarms) × Set Size, where the perceptual sensitivity (the difference between hits and false alarm) is multiplied by set size to take into account the number of to-be-memorized items. The capacity *K* estimated in this way revealed that effectively only 1–2 composite objects could be remembered (see Figure 3b). A repeated-measures ANOVA of the *K* estimates yielded a main effect of interpretation, $F(1, 16) = 23.36$, $p < .0001$, $\eta_p^2 = .593$: significantly more items were maintained with global ($K = 1.45$) as compared to mosaic ($K = 1.28$) representations. No other significant effects were obtained, *ps* > .25.

Figure 3 about here

ERP Data. The corresponding ERP waves for composite objects are plotted in Figure 4a. An ANOVA on the mean CDA amplitudes with the factors set size and interpretation revealed a main effect of interpretation, $F(1, 16) = 6.12$, $p = .025$, $\eta_p^2 = .277$. As depicted in Figure 4b, the mean CDA amplitude was larger for the global (-1.22 μV) as compared to the mosaic interpretation (-.88 μV). No other significant effects were obtained (*p*s > .25). This finding mirrors the pattern of the capacity estimate *K* (Figure 3b), demonstrating an effect of interpretation on the amplitude of the CDA.

The individual differences in the CDA amplitude between global and mosaic interpretations also correlated with the corresponding differences in accuracy (with values averaged across set sizes): $r = -.66$ (95% CI [-.84, -.42]), $p = .004$ (Figure 4c). The statistical significance of the correlation coefficient was determined by comparing the observed correlations with results derived from 10000 permutations of the two variables (i.e., the difference in accuracy and the difference in the CDA amplitude between global and mosaic interpretations). This ensures that the significant correlation is not attributable to any outliers in the data.

Figure 4 about here

Simple Objects

Behavioral Data. Figure 5 displays the mean percentage of correct responses (a) and the corresponding capacity estimates *K* (b) for simple objects as a function of set size, separately for the different interpretations. A repeated-measures ANOVA on the accuracy data with the factor set size and interpretation yielded main effects of set size, $F(1, 16) = 479.30$, $p < .0001$, $\eta_p^2 = .968$, and interpretation, $F(1, 16) = 42.34$, $p < .0001$, $\eta_p^2 = .726$. Accuracy was higher for set size 2 (88%) than for set size 4 (70%), and higher for global (82%) than for mosaic interpretations (77%). The interaction was non-significant, $p > .25$. Moreover, calculation of the capacity estimates *K* (as in the analysis above) again revealed that only 1–2 simple objects could be remembered (see Figure 5b). A repeated-measures ANOVA on the *K* estimates revealed a main effect of interpretation, $F(1, 16) = 26.71$, $p < .0001$, $\eta_p^2 = .625$, with higher capacity for global ($K = 1.73$) than for mosaic interpretations ($K = 1.43$). No other significant effects were obtained, all *ps* > .25.

Figure 5 about here

ERP Data. The corresponding ERP waves for the simple objects in the global and mosaic conditions are plotted in Figure 6. An ANOVA on the mean amplitudes of the CDA with the factors set size and interpretation revealed a main effect of interpretation, $F(1, 16) = 4.77$, $p = .044$, $\eta_p^2 = .230$: of note, the mean CDA amplitude was larger for the mosaic shapes (-1.24 μV) than for the global shapes (-1.00 μV); recall that the reverse pattern was found with composite objects. No other significant effects were obtained (set size, $F(1, 16) = 1.67$, $p = .21$, $\eta_p^2 = .095$; interaction, $F(1, 16) = 1.25$, $p = .28$, $\eta_p^2 = .073$).

Figure 6 about here

Discussion

The present results show that VWM load is directly influenced by processes of object completion given identical physical input. For the composite objects, the behavioral result pattern replicates previous findings (Chen et al., 2016): there was an advantage in representing globally completed over (uncompleted) mosaic interpretations in VWM, where this advantage for completed shapes decreased with an increase in the number of items that were to be memorized. An advantage for global over mosaic interpretations was also evident in the behavioral estimate of memory capacity *K*, which showed that, with the current stimulus material, a maximum of 1 to 2 objects could be successfully retained in VWM. The ERP analyses revealed larger CDA amplitudes for completed versus mosaic representations, for both set sizes, thus mirroring the effect pattern of the *K* estimate. Moreover, the differences in CDA amplitude and behavioral accuracy between completed and mosaic representations were significantly correlated. To our knowledge, these findings provide the first demonstration that VWM load – as measured by the CDA wave – is determined by processes of object completion.

The pattern for simple objects also closely replicated our previous findings (Chen et al., 2016): more regular, symmetric, global shapes led to higher performance than more irregular and complex, mosaic objects. The corresponding CDA analysis for simple objects revealed a larger amplitude for more complex mosaic shapes than for simpler global shapes, thus contrasting with the pattern observed for composite objects (for which the CDA was larger for global than for mosaic objects).

Our simple-object results may be directly compared to previous, related studies that examined how object complexity modulates VWM and the CDA amplitude. For instance, reduced behavioral performance and increased CDA amplitudes were found in a change detection task for rather complex polygon shapes as compared to simpler, colored squares (Alvarez & Cavanagh, 2004; Gao et al., 2009; Luria et al., 2010) – indicative of an increase in perceptual complexity giving rise to increasing VWM demands. That a comparable pattern of results was also found in the present experiment when comparing global and mosaic variants of the simple (non-occluded) objects, confirms that VWM maintenance demands depend on stimulus complexity: less complex global, symmetric objects engender a lower VWM load along with a reduced CDA amplitude compared to more irregular, rather complex mosaic shapes.

Over and above these established effects of perceptual complexity in VWM, our results for composite objects demonstrate a novel link between object completion and memory load. In particular, our findings show that identical perceptual input may lead to differences in the way an object is completed, depending on the prevailing simple-object context. This suggests that observers effectively use past perceptual experience – including long-term familiarity as well as short-term priming – to construct a perceptual representation that, in the global interpretation, incorporates the occluded portions of a given object (Chen et al., 2016).

Evidence for such context-dependent object completions was found in both behavioral performance and the CDA amplitude. Completion of the occluded part of an object to represent a whole renders a more elaborate but at the same time less complex memory representation. Specifically, for global objects, completion resulted in a more regular and symmetric representation, with these simpler shapes in turn yielding an improved performance accuracy compared to uncompleted but more complex shapes in mosaic-type representations (see also van der Helm, 2014). At the neural level, we observed a sustained increase of the CDA amplitude for globally completed objects. While this is in line with the proposal that more elaborate processing, involving mnemonic resources, is required to create complete-object representations from physically specified fragments (Biederman, 1987), it also suggests that persistent mnemonic activity is required to maintain the resulting representations in a readily accessible form (see also Pun, Emrich, Wilson, Stergiopoulos, & Ferber, 2012; Ewerdwalbesloh, Palva, Rösler, & Khader, 2016). Convergent evidence for this proposal is provided by studies that used a shape-from-motion paradigm (Emrich, Ruppel, & Ferber, 2008; Pun et al., 2012). Here, too, the CDA exhibited a sustained increase in amplitude in a task that required an (integrated) object to be extracted and maintained from fragmentary perceptual information. Thus, on this view, the occluded objects engage some additional, completion-related process while being actively maintained in VWM, which is reflected in the increased CDA as compared to the non-completed mosaic representations. Completion, in turn, renders a rather simple object representation, supporting an improvement in performance relative to the more complex mosaic representation. [Of course, completion might, in principle, also generate a relatively complex, non-symmetrical shape (e.g., some form of local shape completion; see Chen et al., 2016), which does not translate into a comparable performance advantage as for the globally completed, symmetric shape.]

In sum, we interpret the observed increase in CDA amplitudes for the global interpretation to reflect the increased demand associated with the imagery process for completing the occluded object parts to represent the whole object, while the observed increase in accuracy for the completed objects derives from the simple and symmetric object representation rendered by this process. This is also reflected in the significant correlation between the completion effect in the CDA amplitude and behavioral accuracy, that is: the advantage for representing completed interpretations in VWM comes at a cost in terms of the mnemonic resources required.

Previous studies have shown that the CDA amplitude increases systematically with the number of objects stored in VWM, up to the maximum load (Vogel & Machizawa, 2004; Luria, Balaban, Awh, & Vogel, 2016, for review). Our results show that the capacity limit in the current experiment is at about 1.5 items, as indicated by the estimates of *K*. Comparable capacity estimates were reported previously for other geometric objects (e.g., Alvarez & Cavanagh, 2004). Owing to this relatively low capacity, at set size 4, the number of to-be-remembered items exceeds the maximum load by more than half, as a result of which only a subset of up to two items is encoded. This is reflected in the CDA being comparable between the two set sizes, that is: the available resources were already maximally invested with 2-item memory displays, so that no further resources could be mustered when the number of to-be-remembered objects was increased to 4 (see also Luria et al., 2010; Gao et al., 2009).

As concerns the limits on the storage capacity of working memory, one view proposes that VWM consists of a pool of resources that can be allocated flexibly to provide either a small number of high-quality representations or a larger number of low-quality representations (Bays & Husain, 2008); by contrast, others have suggested that the number of items that can be stored in VWM is limited and cannot change (Luck & Vogel, 1997; Zhang & Luck, 2008). Here, we found *no* evidence that observers could increase the number of representations by decreasing the quality of the representations in VWM. Instead, we show that, when presented with more objects than the maximum capacity, observers can still store high-quality representations of a subset of the objects, without retaining any information about the others. However, within the limited number of items that can be retained, a variable resource is available to represent the to-be-memorized objects (Nie, Müller, & Conci, 2017; Zhang & Luck, 2008).

In summary, the present study shows that the construction of an integrated object requires VWM resources that depend on structural information of the (to-be-) represented objects: constructing a completed representation from the physically specified parts of the stimulus involves additional mnemonic demands relative to (in terms of information content) uncompleted, mosaic representations. This argues that object representations in VWM are modulated by completion processes, in turn suggesting that the CDA does not only, or simply, reflect the passive retention of items in memory, but also some additional, active processes, or the resource demands associated with these processes, that support the integration of fragmentary parts into wholes. Thus, representing integrated wholes requires mnemonic resources, but with the constructed representations rendering simple and regular shapes, thus enhancing change detection performance.

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Fig. 1. Illustration of the experimental stimuli with their respective composite and simple versions (global and mosaic interpretations). The stimuli were adapted from van Lier et al. (1995), Plomp and van Leeuwen (2006), and Sekuler et al. (1994).

Fig. 2. Trial sequence. Example trial (a) shows a set size 4, composite-object memory display followed by a test display supporting a global interpretation. Participants were instructed to memorize only the stimuli presented on the side indicated by the arrow prior to the memory display. The correct response would be 'same'. Example trial (b) presents a set size 2, simple-object memory display, with global (i.e., symmetric) shapes (correct response: "same"). Note that the example trials in (a) and (b) were presented in the same block (in randomized order), to coherently support a 'global' interpretation of the occluded objects. Example trials (c) and (d) show a composite- and a simple-object memory display with two and four objects, respectively. Displays as depicted in (c) and (d) engender a 'mosaic' interpretation, and were also presented within the same block (correct responses: 'different').

Fig. 3. Mean percentage of correct responses (a) and capacity estimate *K* (b) as a function of memory set size for the different interpretations (global, mosaic) of the composite objects.

Error bars indicate 95% (within-participant) confidence intervals.

Fig. 4. ERP results for composite objects. Panel (a) depicts the grand average ERP waveforms (contralateral minus ipsilateral activity relative to the memorized display hemifield) time-locked to the onset of the memory display at electrodes PO7/8, in the composite-object condition for Set Size 2 (left panel) and Set Size 4 (right panel). Scalp distribution maps depict the point in time at which the respective difference waves reached their maximum. For illustration purposes, the grand average waveforms shown here were low-pass-filtered at 12 Hz (24 dB/Oct). The graph in (b) shows the mean CDA amplitudes in the time window of 500–1200 ms after the onset of the memory display at electrodes PO7/8 as a function of memory set size, separately for the different interpretations (global, mosaic). Error bars indicate 95% (within-participant) confidence intervals. Panel (c) illustrates the correlation between the difference in CDA amplitudes and the corresponding difference in accuracy between global and mosaic interpretations (averaged across set sizes).

Fig. 5. Mean percentage of correct responses (a) and capacity estimate K (b) as a function of memory set size for the different interpretations (global, mosaic) of the simple objects. Error bars denote 95% (within-participant) confidence intervals.

Fig. 6. ERP results for simple objects. Panel (a) depicts the grand average ERP waveforms (contralateral minus ipsilateral activity relative to the memorized display hemifield) time-locked to the onset of the memory display at electrodes PO7/8, in the simple-object

condition for Set Size 2 (left panel) and Set Size 4 (right panel). Scalp distribution maps depict the point in time at which the respective difference waves reached their maximum. For illustration purposes, the grand average waveforms shown here were low-pass-filtered at 12 Hz (24 dB/Oct). The graph in (b) shows mean CDA amplitudes in the time window of 500–1200 ms after the onset of the memory display at electrodes PO7/8 as a function of memory set size, separately for the different interpretations (global, mosaic). Error bars indicate 95% (within-participant) confidence intervals.