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1                   **Object maintenance beyond their visible parts in working memory**

2                   Siyi Chen,<sup>1,2</sup> Thomas Töllner,<sup>1,2</sup> Hermann J. Müller,<sup>1,2,3</sup> Markus Conci<sup>1,2</sup>

3                   <sup>1</sup>*Department of Psychology, Ludwig-Maximilians-Universität München, Germany.*

4                   <sup>2</sup>*Graduate School of Systemic Neurosciences, Ludwig-Maximilians-Universität München,*  
5                   *Germany.*

6                   <sup>3</sup>*Department of Psychological Sciences, Birkbeck College, University of London, UK*

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13                  Correspondence:

14                  Siyi Chen

15                  Allgemeine und Experimentelle Psychologie

16                  Department Psychologie

17                  Ludwig-Maximilians-Universität

18                  Leopoldstr. 13

19                  D-80802 München

20                  Germany

21                  Email: [Siyi.Chen@psy.lmu.de](mailto:Siyi.Chen@psy.lmu.de)

## 22 **Abstract**

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

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

44 **New & Noteworthy**

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

## 52 **Introduction**

53       Amodal completion refers to the phenomenon that occluded parts of an object are  
54 perceptually ‘filled in’ (Michotte, Thines, & Crabbe, 1964/1991), that is, missing information  
55 is (re-) constructed based on the partial physical stimulation available (see Figure 1,  
56 composite, for example stimuli). Representing amodally completed objects has been  
57 suggested to rely on mental imagery (Nanay, 2010). While completion is largely dependent  
58 on the structural properties of a given stimulus (van Lier, van der Helm, & Leeuwenberg,  
59 1994), it may additionally be influenced by background information, such as semantic  
60 knowledge about a given object or the context within which it is presented – providing  
61 further information about what the occluded parts of an object (may) look like (Hazenberg &  
62 van Lier, 2016; Rauschenberger, Peterson, Mosca, & Bruno, 2004). Construction of a mental  
63 image typically engages visual working memory (VWM) resources (Baddeley & Andrade,  
64 2000). On this view, rather than just subserving passive maintenance of visual information for  
65 short periods of time, VWM does also involve active processes of generating (hidden) parts  
66 of objects in memory. The current study was designed to investigate such active object  
67 completion processes in VWM, that is, to elucidate how physically specified parts of a  
68 stimulus are combined with completed fragments to generate a coherent, whole-object  
69 representation.

70       A common and widely used paradigm for studying VWM is change detection (Luck &  
71 Vogel, 1997). In this paradigm, participants are asked to remember a set of objects in an  
72 initial memory display. After a retention interval, a test display is presented and participants  
73 have to indicate whether a change has occurred in one of the objects in the test as compared

74 to the memory array. The typical finding is that some three to four objects can be maintained  
75 concurrently in VWM (Luck & Vogel, 1997; Cowan, 2001). However, the number of items  
76 that can be stored has also been shown to be influenced by the information load associated  
77 with the individual, to-be-memorized objects. For instance, Alvarez and Cavanagh (2004)  
78 demonstrated that change detection performance varies as a function of stimulus complexity,  
79 with a reduced number of only about one memorized item for more complex objects (e.g.,  
80 Chinese characters, shaded cubes), as compared to four items for more simple objects (e.g.,  
81 colored squares). Thus, VWM is limited in capacity: it can represent only relatively few items,  
82 where the overall number of items that can be retained varies for different types of objects.

83       Studies that examined participants' electroencephalogram (EEG) in change detection  
84 tasks showed that an event-related difference wave manifesting during the delay period  
85 (between the memory and test displays) over lateral posterior parietal and occipital electrode  
86 sites – referred to as 'contralateral delay activity' (CDA) – can serve as an online marker of  
87 current VWM load: the CDA amplitude increases with the number of items (to be) held in  
88 memory, until reaching an asymptotic limit indicative of an individual's memory capacity  
89 (Vogel & Machizawa, 2004). Given that the CDA (which is obtained in the delay period)  
90 reflects processes of maintenance (independent of later processes involved in the comparison  
91 of the memorized items with the test probe; see Awh, Barton, & Vogel, 2007), it can be used  
92 to directly examine how stimuli are represented in VWM. For instance, with relatively few  
93 to-be-memorized items, CDA amplitudes were found to be larger for more complex (random  
94 polygons) than for simple objects (colored squares) – in line with the view that VWM is  
95 modulated by stimulus attributes and the load they place on processes of maintenance (Luria,

96 Sessa, Gotler, Jolicœur, & Dell'Acqua, 2010; Gao et al., 2009; Töllner, Conci, Rusch, &  
97 Müller, 2013). Moreover, larger CDA amplitudes were observed for identical stimuli when  
98 the task required the encoding of objects with high precision (Machizawa, Goh, & Driver,  
99 2012). This demonstrates that identical visual input may change the memory load depending  
100 on top-down demands (see also Balaban & Luria, 2016). Nevertheless, it remains an open  
101 issue whether the CDA varies with the extent to which processes of completion modify a  
102 given object in VWM.

103         The question at issue here, namely: the role of object completion in VWM, was recently  
104 examined in a behavioral study employing the change detection paradigm (Chen, Müller, &  
105 Conci, 2016). Chen et al. presented memory displays that were physically identical, but  
106 varied the structural information of the objects' representations in memory by introducing  
107 additional, contextual information. The memory displays participants were presented with  
108 were essentially comparable to the example displays depicted in Figure 2 (except that, in  
109 Chen et al., 2016, participants were not pre-cued to the task-relevant side of the display by an  
110 arrow symbol). A given memory display consisted either of composite objects (i.e.,  
111 presenting a notched figure adjacent to a square) or of simple objects (i.e., comparable shapes  
112 but without the adjacent square). Importantly, the simple object could be one of several  
113 possible interpretations of the notched figure, with a global, symmetrical shape that provides  
114 a completed interpretation of the composite object (Figure 1, global), or a so-called 'mosaic'  
115 figure (Figure 1, mosaic), where mosaic simply refers to a 2-D cut-out outline shape identical  
116 to the visible part of the figure (Sekuler & Palmer, 1992). Presentation of the memory display  
117 was followed by a brief delay, after which a (simple-object) test probe appeared. The task was

118 to decide whether this probe was the same as or different from the corresponding item in the  
119 memory display. Each block of trials presented only one type of (simple) objects (either  
120 global or mosaic figures), to enforce, or ‘prime’, a consistent interpretation of the composite  
121 objects within the given block. The results revealed global objects to yield higher change  
122 detection accuracy, indicative of an advantage in retaining completed wholes over partial  
123 shapes (Chen et al., 2016, Experiment 1). This advantage for completed, relative to mosaic,  
124 *composite* objects disappeared when global and mosaic *simple* object displays were presented  
125 randomly intermixed within trial blocks (Chen et al., 2016, Experiment 2), indicating that the  
126 effect of completion is determined by some top-down set provided by a consistent context of  
127 the available simple object interpretations.

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

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

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

161

## 162 **Method**

### 163 **Participants**

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

### 171 **Apparatus and Stimuli**

172 Stimuli were black line drawings ( $0.2 \text{ cd/m}^2$ ) presented against a light gray background  
173 ( $178 \text{ cd/m}^2$ ) on a 19-inch computer monitor ( $1024 \times 768$  pixel screen resolution, 85-Hz  
174 refresh rate). The stimulus set was based on six different shapes (adapted from van Lier et al.,  
175 1995; Plomp & van Leeuwen, 2006; Sekuler, Palmer, & Flynn, 1994; see Figure 1). The  
176 composite figure included a square with a second shape positioned partly occluded next to the  
177 square (Figure 1, Composite). The simple figure was presented in two possible alternative  
178 interpretations of the composite object: global and mosaic (Figure 1, Simple-Global,  
179 Simple-Mosaic). Global figures presented a globally completed, symmetrical shape, whereas  
180 a mosaic figure simply presented a 2-D cutout outline shape identical to the visible part of the  
181 partly occluded figure. At a viewing distance of 60 cm, each simple figure touched a circular  
182 region with a radius of  $0.6^\circ$  of visual angle. The square of the occluded objects subtended  
183  $1.1^\circ \times 1.1^\circ$ . For each memory display, four or eight distinct objects of the same completion

184 type were presented randomly at ten positions within a circular region with a radius of  $5.0^\circ$ ,  
185 with two or four objects in each hemifield. A given shape could appear only twice at most in  
186 the same display. The test probe was identical to the item in the same position of the memory  
187 display in half the trials and different in the other half. It should be noted that "same" or  
188 "different" in this experiment refers to object identity, rather than to the completion type. For  
189 example, the occluded cross in Figure 1a (Composite) would be considered the same object  
190 as the other two variants of simple objects presenting a cross-shaped item (Figure 1a,  
191 Simple).

## 192 **Procedure and Design**

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

205 There were eight experimental blocks, with 160 trials each. Each block presented only

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

212 *Figure 1 about here*

213 *Figure 2 about here*

214

## 215 **EEG Recording and Data Analysis**

216 The EEG was continuously recorded using 64 Ag/AgCl active electrodes (Brain  
217 Products Munich) according to the international 10-10 System with a sampling rate of 1000  
218 Hz. Vertical and horizontal eye movements were monitored with electrodes placed at the  
219 outer canthi of the eyes, and respectively, the superior and inferior orbits. The electrode  
220 signals were amplified using BrainAmp amplifiers (BrainProducts, Munich) with a 0.1 –  
221 250-Hz bandpass filter. All electrode impedances were kept below 5 k $\Omega$ . During data  
222 acquisition, all electrodes were referenced to FCz, and re-referenced off-line to averaged  
223 mastoids. Prior to segmenting the EEG, the raw data was visually inspected in order to  
224 manually remove nonstereotypical noise. Next, an infomax-independent component analysis  
225 was run to identify components representing blinks and horizontal eye movements, and to  
226 remove these artifacts before backprojection of the residual components. Subsequently, the  
227 data were band-pass filtered using a 0.1 – 40-Hz Butterworth IIR filter (24 dB/Oct). Signals  
228 were then averaged off-line over a 1200-ms epoch relative to a 200-ms pre-stimulus (memory

229 display) baseline. Trials with artifacts –defined as any signal exceeding  $\pm 60 \mu\text{V}$ , bursts of  
230 electromyographic activity (as defined by voltage steps/sampling point larger than  $50 \mu\text{V}$ )  
231 and activity lower than  $0.5 \mu\text{V}$  within intervals of 500 ms (indicating bad channels) – were  
232 excluded from averaging. The contralateral delay activity (CDA) was measured at  
233 parieto-occipital electrodes (PO7/8) as the difference in mean amplitude between the  
234 ipsilateral and contralateral waveforms relative to the memorized display, with a  
235 measurement window of 500–1200 ms after the onset of the memory display. Trials with  
236 incorrect behavioral responses were discarded from the ERP analyses.

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

247

## 248 **Results**

### 249 **Composite Objects**

250 Behavioral Data. Figure 3a depicts the mean percentage of correct responses for

251 composite objects as a function of set size, separately for the different interpretations. A  
252 repeated-measures ANOVA on the accuracy data was performed with the factors set size and  
253 interpretation, yielding main effects of set size,  $F(1, 16) = 767.07, p < .0001, \eta_p^2 = .980$ , and  
254 interpretation,  $F(1, 16) = 39.06, p < .0001, \eta_p^2 = .709$ . Accuracy was higher for set size 2  
255 (84%) than for set size 4 (67%), and higher for global (77%) than for mosaic interpretations  
256 (74%). The interaction between set size and interpretation was also significant,  $F(1, 16) =$   
257  $11.62, p = .004, \eta_p^2 = .421$ : a significant difference between global (86%) and mosaic  
258 interpretations (81%) manifested with set size 2,  $t(16) = 6.66, p < .0001$ , while this difference  
259 was reduced for set size 4 (global: 68%; mosaic: 67%),  $t(16) = 1.88, p = .078$ . Replicating our  
260 previous findings (Chen et al., 2016), this reduction in performance can be attributed to the  
261 reduced scanning time available per object with an increased set size. As a result, not all  
262 objects are effectively completed for the larger, 4-item display. With larger memory arrays,  
263 there would then also be a higher chance of guessing, as attention is less likely focused on the  
264 object that is tested later on – so that this item might not have been encoded with sufficient  
265 detail. Moreover, accuracy might also be compromised by errors arising from the comparison  
266 of an item held in memory with the test probe presented (Awh et al., 2007), and these  
267 comparison errors might also increase with set size.

268 In a next step, we computed Cowan's  $K$  (Cowan, 2001), an estimate of visual memory  
269 capacity, which allows correcting for errors that result from memory storage failures. Note,  
270 however, that  $K$  does not take care of errors arising from the comparison process – which is  
271 why  $K$  might somewhat underestimate the number of items stored (though this  
272 underestimation should be comparable for global and mosaic interpretations). Essentially, this

273 correction assumes that if an observer can hold  $K$  items in memory from an array of  $S$  items,  
274 the item that changed should be one of the items being held in memory on  $K/S$  trials, resulting  
275 in correct performance on  $K/S$  of the trials on which an item changed.  $K$  is computed  
276 according to the formula: (Proportion Hits – Proportion False Alarms)  $\times$  Set Size, where the  
277 perceptual sensitivity (the difference between hits and false alarm) is multiplied by set size to  
278 take into account the number of to-be-memorized items. The capacity  $K$  estimated in this way  
279 revealed that effectively only 1–2 composite objects could be remembered (see Figure 3b). A  
280 repeated-measures ANOVA of the  $K$  estimates yielded a main effect of interpretation,  $F(1, 16)$   
281  $= 23.36, p < .0001, \eta_p^2 = .593$ : significantly more items were maintained with global ( $K =$   
282  $1.45$ ) as compared to mosaic ( $K = 1.28$ ) representations. No other significant effects were  
283 obtained,  $ps > .25$ .

284 *Figure 3 about here*

285  
286 ERP Data. The corresponding ERP waves for composite objects are plotted in Figure 4a.  
287 An ANOVA on the mean CDA amplitudes with the factors set size and interpretation revealed  
288 a main effect of interpretation,  $F(1, 16) = 6.12, p = .025, \eta_p^2 = .277$ . As depicted in Figure 4b,  
289 the mean CDA amplitude was larger for the global ( $-1.22 \mu\text{V}$ ) as compared to the mosaic  
290 interpretation ( $-.88 \mu\text{V}$ ). No other significant effects were obtained ( $ps > .25$ ). This finding  
291 mirrors the pattern of the capacity estimate  $K$  (Figure 3b), demonstrating an effect of  
292 interpretation on the amplitude of the CDA.

293 The individual differences in the CDA amplitude between global and mosaic  
294 interpretations also correlated with the corresponding differences in accuracy (with values

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

301 *Figure 4 about here*

302

### 303 **Simple Objects**

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

316

*Figure 5 about here*

317

318 ERP Data. The corresponding ERP waves for the simple objects in the global and  
319 mosaic conditions are plotted in Figure 6. An ANOVA on the mean amplitudes of the CDA  
320 with the factors set size and interpretation revealed a main effect of interpretation,  $F(1, 16) =$   
321  $4.77, p = .044, \eta_p^2 = .230$ : of note, the mean CDA amplitude was larger for the mosaic shapes  
322  $(-1.24 \mu V)$  than for the global shapes  $(-1.00 \mu V)$ ; recall that the reverse pattern was found  
323 with composite objects. No other significant effects were obtained (set size,  $F(1, 16) = 1.67, p$   
324  $= .21, \eta_p^2 = .095$ ; interaction,  $F(1, 16) = 1.25, p = .28, \eta_p^2 = .073$ ).

325 *Figure 6 about here*

326

## 327 **Discussion**

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

340 first demonstration that VWM load – as measured by the CDA wave – is determined by  
341 processes of object completion.

342 The pattern for simple objects also closely replicated our previous findings (Chen et al.,  
343 2016): more regular, symmetric, global shapes led to higher performance than more irregular  
344 and complex, mosaic objects. The corresponding CDA analysis for simple objects revealed a  
345 larger amplitude for more complex mosaic shapes than for simpler global shapes, thus  
346 contrasting with the pattern observed for composite objects (for which the CDA was larger  
347 for global than for mosaic objects).

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

359 Over and above these established effects of perceptual complexity in VWM, our results  
360 for composite objects demonstrate a novel link between object completion and memory load.  
361 In particular, our findings show that identical perceptual input may lead to differences in the

362 way an object is completed, depending on the prevailing simple-object context. This suggests  
363 that observers effectively use past perceptual experience – including long-term familiarity as  
364 well as short-term priming – to construct a perceptual representation that, in the global  
365 interpretation, incorporates the occluded portions of a given object (Chen et al., 2016).

366 Evidence for such context-dependent object completions was found in both behavioral  
367 performance and the CDA amplitude. Completion of the occluded part of an object to  
368 represent a whole renders a more elaborate but at the same time less complex memory  
369 representation. Specifically, for global objects, completion resulted in a more regular and  
370 symmetric representation, with these simpler shapes in turn yielding an improved  
371 performance accuracy compared to uncompleted but more complex shapes in mosaic-type  
372 representations (see also van der Helm, 2014). At the neural level, we observed a sustained  
373 increase of the CDA amplitude for globally completed objects. While this is in line with the  
374 proposal that more elaborate processing, involving mnemonic resources, is required to create  
375 complete-object representations from physically specified fragments (Biederman, 1987), it  
376 also suggests that persistent mnemonic activity is required to maintain the resulting  
377 representations in a readily accessible form (see also Pun, Emrich, Wilson, Stergiopoulos, &  
378 Ferber, 2012; Ewerdwalbesloh, Palva, Rösler, & Khader, 2016). Convergent evidence for this  
379 proposal is provided by studies that used a shape-from-motion paradigm (Emrich, Ruppel, &  
380 Ferber, 2008; Pun et al., 2012). Here, too, the CDA exhibited a sustained increase in  
381 amplitude in a task that required an (integrated) object to be extracted and maintained from  
382 fragmentary perceptual information. Thus, on this view, the occluded objects engage some  
383 additional, completion-related process while being actively maintained in VWM, which is

384 reflected in the increased CDA as compared to the non-completed mosaic representations.  
385 Completion, in turn, renders a rather simple object representation, supporting an  
386 improvement in performance relative to the more complex mosaic representation. [Of course,  
387 completion might, in principle, also generate a relatively complex, non-symmetrical shape  
388 (e.g., some form of local shape completion; see Chen et al., 2016), which does not translate  
389 into a comparable performance advantage as for the globally completed, symmetric shape.]

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

398 Previous studies have shown that the CDA amplitude increases systematically with the  
399 number of objects stored in VWM, up to the maximum load (Vogel & Machizawa, 2004;  
400 Luria, Balaban, Awh, & Vogel, 2016, for review). Our results show that the capacity limit in  
401 the current experiment is at about 1.5 items, as indicated by the estimates of  $K$ . Comparable  
402 capacity estimates were reported previously for other geometric objects (e.g., Alvarez &  
403 Cavanagh, 2004). Owing to this relatively low capacity, at set size 4, the number of  
404 to-be-remembered items exceeds the maximum load by more than half, as a result of which  
405 only a subset of up to two items is encoded. This is reflected in the CDA being comparable

406 between the two set sizes, that is: the available resources were already maximally invested  
407 with 2-item memory displays, so that no further resources could be mustered when the  
408 number of to-be-remembered objects was increased to 4 (see also Luria et al., 2010; Gao et  
409 al., 2009).

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

422 In summary, the present study shows that the construction of an integrated object  
423 requires VWM resources that depend on structural information of the (to-be-) represented  
424 objects: constructing a completed representation from the physically specified parts of the  
425 stimulus involves additional mnemonic demands relative to (in terms of information content)  
426 uncompleted, mosaic representations. This argues that object representations in VWM are  
427 modulated by completion processes, in turn suggesting that the CDA does not only, or simply,

428 reflect the passive retention of items in memory, but also some additional, active processes,  
429 or the resource demands associated with these processes, that support the integration of  
430 fragmentary parts into wholes. Thus, representing integrated wholes requires mnemonic  
431 resources, but with the constructed representations rendering simple and regular shapes, thus  
432 enhancing change detection performance.

433

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437

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514

515

516

517 **Fig. 1.** Illustration of the experimental stimuli with their respective composite and simple  
518 versions (global and mosaic interpretations). The stimuli were adapted from van Lier et al.  
519 (1995), Plomp and van Leeuwen (2006), and Sekuler et al. (1994).

520

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

531

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

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

535

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

548

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

552

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

556 condition for Set Size 2 (left panel) and Set Size 4 (right panel). Scalp distribution maps  
557 depict the point in time at which the respective difference waves reached their maximum. For  
558 illustration purposes, the grand average waveforms shown here were low-pass-filtered at 12  
559 Hz (24 dB/Oct). The graph in (b) shows mean CDA amplitudes in the time window of  
560 500–1200 ms after the onset of the memory display at electrodes PO7/8 as a function of  
561 memory set size, separately for the different interpretations (global, mosaic). Error bars  
562 indicate 95% (within-participant) confidence intervals.