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4

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6 **Independent attention mechanisms for tactile and visual working**  
7 **memory**

8

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13

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15

16 **Keywords**

- 17 • Working memory (WM)
- 18 • Selective Attention
- 19 • Multisensory (tactile / visual)
- 20 • Electroencephalography (EEG)

21 **Abstract.** Working memory (WM) is limited in capacity, but it is controversial whether these  
22 capacity limitations are domain-general or are generated independently within separate  
23 modality-specific memory systems. These alternative accounts were tested in bimodal  
24 visual/tactile WM tasks. In Experiment 1, participants memorized the locations of  
25 simultaneously presented task-relevant visual and tactile stimuli. Visual and tactile WM load  
26 was manipulated independently (1, 2 or 3 items per modality), and one modality was  
27 unpredictably tested after each trial. To track the activation of visual and tactile WM  
28 representations during the retention interval, the visual and tactile contralateral delay activity  
29 (CDA and tCDA) were measured over visual and somatosensory cortex, respectively. CDA  
30 and tCDA amplitudes were selectively affected by WM load in the corresponding (tactile or  
31 visual) modality. The CDA parametrically increased when visual load increased from 1 to 2 and  
32 to 3 items. The tCDA was enhanced when tactile load increased from 1 to 2 items, and  
33 showed no further enhancement for 3 tactile items. Critically, these load effects were strictly  
34 modality-specific, as substantiated by Bayesian statistics. Increasing tactile load did not affect  
35 the visual CDA, and increasing visual load did not modulate the tCDA. Task performance at  
36 memory test was also unaffected by WM load in the other (untested) modality. This was  
37 confirmed in a second behavioral experiment where tactile and visual loads were either two or  
38 four items, unimodal baseline conditions were included, and participants performed a color  
39 change detection task in the visual modality. These results show that WM capacity is not  
40 limited by a domain-general mechanism that operates across sensory modalities. They  
41 suggest instead that WM storage is mediated by distributed modality-specific control  
42 mechanisms that are activated independently and in parallel during multisensory WM.

44

## 45 **Introduction**

46 Working memory (WM) refers to the ability to memorize stimuli over brief periods of  
47 time. The most notable feature of WM is its limited capacity, as only 3-4 items can be  
48 successfully maintained in WM (Cowan, 2001; Vogel & Machizawa, 2004). The reasons for  
49 these capacity limitations are still under dispute. They may either arise at a central domain-  
50 unspecific level, or may be generated independently within separate domain-specific storage  
51 systems that represent a particular type of information (e.g., visual, auditory, or tactile items).  
52 The domain-unspecific account assumes that the limited capacity of WM reflects the limited  
53 availability of an attention resource that is shared across sensory modalities, and/or the  
54 existence of a central storage system (Cowan, 2011). In this case, the same capacity  
55 limitations would apply regardless of whether memorized items have been encoded through  
56 the same modality or through different modalities. Alternatively, if the maintenance of items  
57 from different modalities is mediated by distributed processes that operate independently at  
58 peripheral modality-specific levels (Tamber-Rosenau & Marois, 2016), WM capacity limitations  
59 should occur within – but not across – sensory modalities.

60 The question whether WM capacity limits arise at domain-general or domain-specific  
61 levels can be tested in multimodal dual-task experiments, where participants simultaneously  
62 memorize sets of stimuli from different modalities (e.g., visual and auditory items), and dual-  
63 task interference (i.e., performance decrements in one modality due to WM load increments in  
64 another modality) is measured. Crossmodal interference effects were found in numerous  
65 auditory-visual experiments (Cocchini, Logie, Della Sala, MacPherson, & Baddeley, 2002;  
66 Cowan, Saults, & Blume, 2014; Fougne & Marois, 2011; Morey & Cowan, 2005; Salmela,

67 Moissala, & Alho, 2014; Saults & Cowan, 2007), but the theoretical implications of such effects  
68 remain disputed. Some authors have interpreted interference as evidence for a WM store  
69 and/or attention mechanism that is shared across sensory modalities (Cowan, 2010; Cowan,  
70 2011; Cowan et al., 2014; Saults & Cowan, 2007). Others assume that interference in  
71 multimodal WM tasks does not reflect a cognitive bottleneck that is specific to WM storage, but  
72 instead results from general dual-task coordination costs (e.g., Cocchini et al., 2002). The  
73 amount of interference between items from different modalities also varies considerably across  
74 previous studies. Experiments that found strong interference led to the conclusion that WM  
75 maintenance is mediated by a central mechanism (Saults & Cowan, 2007), whereas studies  
76 that only found weak interference (Cocchini et al., 2002), or no interference at all (Fougnie,  
77 Zughni, Godwin, & Marois, 2015), suggest that WM maintenance relies on processes that are  
78 inherently modality-specific. A third possibility is that WM capacity is constrained by both  
79 central and modality-specific mechanisms (Cowan et al., 2014; Fougnie & Marois, 2011).

80 Evidence that modality-specific mechanisms underpin WM maintenance comes from  
81 neuroimaging studies showing that stimulus representations are stored in the same cortical  
82 areas that have encoded these stimuli into WM (“sensory recruitment hypothesis” Emrich,  
83 Riggall, LaRocque, & Postle, 2013; Jonides, Lacey, & Nee, 2005; Pasternak & Greenlee,  
84 2005). Modality-specific sources of WM capacity limits were identified by studies that predicted  
85 visual WM capacity based on the size of primary visual cortex (Bergmann, Genc, Kohler,  
86 Singer, & Pearson, 2016), or by the amplitude of the contralateral delay activity (CDA, e.g.,  
87 McCollough, Machizawa, & Vogel, 2007; Vogel & Machizawa, 2004) over visual cortex. The  
88 CDA component emerges in the EEG over posterior visual areas during the retention period of  
89 lateralized visual WM tasks. The somatosensory analogue of the CDA has recently been

90 identified in tactile WM experiments (Katus & Eimer, 2015; Katus & Müller, 2016; Katus,  
91 Müller, & Eimer, 2015b). During the maintenance of lateralized tactile stimuli, a tactile CDA  
92 component (tCDA) is elicited with a topographical distribution over somatosensory cortex.  
93 Thus, the CDA and tCDA reflect the activation of WM representations in modality-specific  
94 visual and somatosensory cortical areas, respectively. Because both components are sensitive  
95 to WM load and WM capacity limits (Katus, Grubert, & Eimer, 2015a; Vogel & Machizawa,  
96 2004), co-registering them in bimodal visual-tactile WM tasks allows for testing whether WM  
97 capacity limitations are shared across sensory modalities, or whether they arise independently  
98 within modality-specific storage systems. The simultaneous measurement of the tCDA/CDA  
99 components in tactile/visual WM tasks (Katus & Eimer, 2016; Katus, Grubert, & Eimer, 2017) is  
100 feasible after transforming EEG data to current source densities (CSDs, Tenke & Kayser,  
101 2012). Combining behavioral and EEG measures in investigations of WM capacity limits is  
102 important because behavioral performance may reflect not only WM storage but also other  
103 capacity-unrelated processes, such as the comparison between memorized and test items  
104 (Awh, Barton, & Vogel, 2007). In contrast, CDA components provide on-line measures of WM  
105 maintenance that are unaffected by subsequent memory comparison or response selection  
106 processes. A pattern of results where crossmodal interference effects are observed for  
107 performance but not for visual and tactile CDAs would therefore suggest that these effects  
108 were generated at later storage-unrelated stages.

109 In Experiment 1, participants performed a lateralized dual-task where visual and tactile  
110 items were presented simultaneously in the left and right visual field and to the left and right  
111 hand. All items on one side had to be memorized, and WM load was manipulated orthogonally  
112 in vision and touch. The critical question was whether the maintenance of visual and tactile

113 items in WM is mediated by a shared central process, or by independent modality-specific  
114 mechanisms. A recent behavioral dual-task experiment that required memory for visual colors  
115 and auditorily presented digits found no crossmodal interactions (e.g., Experiments 1-7 in  
116 Fougnie et al., 2015), consistent with the assumption that maintenance operates in a modality-  
117 specific fashion. However, such processes might operate independently for different types of  
118 content within each modality (Fougnie & Alvarez, 2011; Shin & Ma, 2017; Wheeler &  
119 Treisman, 2002). For this reason, Experiment 1 employed a multisensory WM task where  
120 participants memorized spatial locations in vision and touch. Although locations are  
121 represented in different formats in these modalities (retinotopic or spatiotopic in vision,  
122 somatotopic in touch), combining visual and tactile spatial WM tasks may still increase the  
123 representational overlap between multisensory information in WM (Tamber-Rosenau & Marois,  
124 2016) relative to situations where different feature dimensions have to be memorized in  
125 different modalities.

126 On each trial, participants had to memorize the locations of 1, 2, or 3 visual items, and  
127 of 1, 2, or 3 tactile items, and memory was unpredictably tested for either modality after the  
128 trial. This design allowed us to simultaneously test the effects of increasing WM load within  
129 and across modalities on behavioral and electrophysiological measures of WM storage. The  
130 number of visual or tactile items that have to be retained should affect performance on trials  
131 where the respective modality is tested, with a reduction in accuracy with increased WM load.  
132 Increasing visual and tactile WM load should also be reflected by CDA and tCDA amplitudes.  
133 Previous unimodal studies have found load-dependent CDA enhancements for set sizes up to  
134 3 visual items (Vogel & Machizawa, 2004), and tCDA enhancements for load increments from

135 1 to 2 tactile items (Katus et al., 2015a). Similar modality-specific load effects should also be  
136 found in Experiment 1.

137         The critical question was whether in addition to these modality-specific effects, there  
138 would be additional costs associated with the manipulation of WM load in the other modality.  
139 Domain-general accounts (e.g., Cowan, 2011; Saults & Cowan, 2007) assume that the  
140 capacity of visual and tactile WM is limited by a shared central mechanism, and that the  
141 capacity limit of 3-4 items found for unimodal WM (Cowan, 2001; Vogel & Machizawa, 2004)  
142 also determines the maximum number of items that can be simultaneously maintained in  
143 multisensory WM tasks. If this is correct, behavioral and electrophysiological crossmodal load  
144 effects should be observed in Experiment 1 when more than 3-4 multisensory items have to be  
145 memorized simultaneously. When vision is tested, WM performance should differ as a function  
146 of the number of tactile items that are simultaneously maintained, with crossmodal costs on  
147 trials with higher tactile load. Analogous crossmodal costs of increased visual load should be  
148 observed on trials where tactile WM is tested. In addition, visual CDA components should be  
149 affected by concurrent tactile WM load, with reduced components when tactile load is  
150 increased, and vice versa for tactile CDA components and visual load. In contrast, if the  
151 maintenance of visual and tactile WM representations operates in an entirely modality-specific  
152 fashion, no such crossmodal interference effects should be observed. Load manipulations in  
153 vision and touch should produce strictly modality-specific behavioral and electrophysiological  
154 effects, but there should be no impact of visual load on tactile WM performance and tCDA  
155 components, and no effect of tactile load on visual WM performance and CDA components.  
156 Because this domain-specific account predicts crossmodal null effects that cannot be  
157 confirmed by conventional significance tests (which only allow for rejecting the null



158 hypothesis), we assessed the statistical reliability of null effects using Bayesian statistics  
159 (Rouder, Morey, Verhagen, Swagman, & Wagenmakers, 2017; Rouder, Speckman, Sun,  
160 Morey, & Iverson, 2009).

161

## 162 **Experiment 1**

163

### 164 **Materials and methods**

165 **Participants** The sample size was 30 participants (average age 28y, 19 female, 28 right-  
166 handed) after exclusion of 4 participants with excessive EEG artefacts. All participants were  
167 neurologically unimpaired and gave informed written consent prior to testing. The experiment  
168 was conducted in accordance with the Declaration of Helsinki, and was approved by the  
169 Psychology Ethics Committee, Birkbeck, University of London.

170

171 **Stimulus material** Participants were seated in a dimly lit recording chamber with their hands  
172 covered from sight. All stimuli were presented for 200 ms. Tactile stimuli (100 Hz sinusoids,  
173 intensity 0.37 N) were delivered by eight mechanical stimulators that were attached to the left  
174 and right hands' distal phalanges of the index, middle, ring and little fingers. The stimulators  
175 were driven by custom-built amplifiers, controlled by MATLAB routines (The MathWorks,  
176 Natick, USA) via an eight-channel sound card (M-Audio, Delta 1010LT). Headphones played  
177 continuous white noise to mask any sounds produced by tactile stimulation. Visual stimuli were  
178 shown at a viewing distance of 100 cm against a dark grey background on a 22 inch monitor  
179 (Samsung SyncMaster 2233; 100 Hz refresh rate, 16 ms response time). Throughout the

180 experiments, the monitor showed black crosshairs (three lines at 0°, 45° and 90° polar angle;  
181 horizontal/vertical eccentricity: 3.44° of visual angle) and three concentric black rings around  
182 the fixation dot (eccentricity: 3.15° outer ring, 2.21° middle ring, 1.26° inner ring); see Figure 1.  
183 Stimuli shown on different rings had different sizes, which decreased from lateral to medial  
184 (0.40°, 0.34°, 0.28° for stimuli on the outer, middle and inner ring, respectively). A headset  
185 microphone recorded vocal responses (“a” for match and “e” for mismatch, see below) during  
186 the 1800 ms period after the trial.

187

188 -----

189 Insert Figure 1 here

190 -----

191

192 **Experimental conditions** The experiment comprised 720 trials, run in 16 blocks. Participants  
193 were instructed to memorize the tactile/visual samples on the same side, left or right. The task-  
194 relevant side (left or right) was randomized per participant for the first block, remained constant  
195 for blocks 1-8, and then changed to the opposite side for blocks 9-16. WM load (1, 2 or 3  
196 items) varied on a trial-basis independently for each modality, resulting in 9 load conditions  
197 with 80 trials each. Memory was unpredictably assessed with a tactile or visual test set,  
198 resulting in 40 trials per condition where memory was tested for touch and vision. Training was  
199 run before the experiment (depending on individual performance between 40-80 trials).  
200 Feedback about the proportion of correct responses was given after each block.

201

202 **Stimulation and randomization procedure.** In each trial, tactile and visual stimuli were  
203 simultaneously presented for the bimodal sample set, which was followed by a unimodal test  
204 set after 1s. Depending on tactile load ( $N_T$ ), we separately selected  $N_T$  locations for the tactile  
205 samples on the left and right side. Tactile tests comprised one stimulus per hand, presented to  
206 the same location as a sample, or to a different location (match/mismatch, 50% each).  
207 Depending on visual load ( $N_V$ ), we separately selected  $N_V$  locations for the visual samples on  
208 the left and right side. These locations were sampled from 110 angular positions (in polar  
209 coordinates, left side:  $125^\circ$  to  $234^\circ$ , right side:  $305^\circ$  to  $54^\circ$ ), with the constraint that the  
210 sampled positions were at least  $25^\circ$  apart. We randomly formed  $N_V$  pairs of left- and right-sided  
211 positions, and assigned these coordinate pairs to the same concentric ring ( $N_V$  rings were  
212 selected without replacement to ensure that no ring contained more than 2 stimuli, i.e., 1 per  
213 side). Each visual test stimulus matched the location of a sample on half of all trials and  
214 appeared at a different location on the other half ( $30^\circ$  angular offset relative to the location of a  
215 randomly selected sample). Regardless of whether memory was tested for touch or vision,  
216 matches/mismatches between sample and test were not correlated for the left and right sides.

217

218 **Acquisition and pre-processing** EEG data, sampled at 500 Hz using a BrainVision amplifier,  
219 were DC-recorded from 64 Ag/AgCl active electrodes at standard locations of the extended 10-  
220 20 system. Two electrodes at the eyes' outer canthi monitored horizontal eye movements  
221 (horizontal electrooculogram, HEOG). Continuous EEG data were referenced to the left  
222 mastoid during recording, and re-referenced to the arithmetic mean of both mastoids for data  
223 pre-processing. Data were offline submitted to a 20 Hz low-pass filter (Blackman window, filter

224 order 1000). Epochs were extracted for the 1s period after the sample set, and were corrected  
225 for a 200 ms pre-stimulus baseline.

226

227 **Artefact rejection and correction** Trials with saccades were rejected using a differential step  
228 function that ran on the bipolarized HEOG (step width 200 ms, threshold 30  $\mu\text{V}$ ). *Independent*  
229 *Component Analysis* (ICA) (Delorme, Sejnowski, & Makeig, 2007) was subsequently used to  
230 correct for frontal artefacts such as eye blinks, and residual traces of horizontal eye  
231 movements that had not been detected by the step function. We rejected trials in which  
232 difference values for corresponding left- minus right-hemispheric electrodes exceeded a fixed  
233 threshold of  $\pm 50 \mu\text{V}$  (for any electrode pair). We furthermore excluded epochs with unusual  
234 spectral profiles; using fast Fourier transforms, we calculated the power of difference values for  
235 5 frequency bins (between 1 and 9 Hz) for each trial and electrode pair. Spectral power was  
236 normalized across trials by means of z-transforms. An epoch was rejected if z-scores  
237 exceeded 3 (for any frequency bin and electrode pair). Notably, this procedure was only used  
238 to identify epochs with artefacts; the z-scores were discarded after artefact rejection, and  
239 played no role in any statistical analysis. Epochs entered *Fully Automated Statistical*  
240 *Thresholding for EEG Artefact Rejection* (FASTER, Nolan, Whelan, & Reilly, 2010) for the  
241 interpolation of noisy electrodes, and were subsequently converted to current source densities  
242 (CSDs: iterations = 50, m = 4, lambda =  $10^{-5}$ ; Tenke & Kayser, 2012). 93.0% of epochs  
243 remained for statistical analysis. Statistical tests were based on correct and incorrect trials; the  
244 exclusion of incorrect trials did not change the pattern of results, but would have reduced the  
245 signal-to-noise ratio of EEG data.

246

247 **Selection of electrodes and time windows; topographical maps** We separately averaged  
248 CSDs across three adjacent electrodes contralateral and ipsilateral to the task-relevant side.  
249 As in prior studies (Katus et al., 2017; Katus & Eimer, 2016), the tactile and visual CDA  
250 components were measured at lateral central (tCDA: C3/4, FC3/4, CP3/4) and occipital scalp  
251 regions (CDA: PO7/8, PO3/4, O1/2). Statistical tests were conducted on difference values of  
252 contra- minus ipsilateral CSDs averaged between 300 and 1000 ms after the sample set (cf.  
253 Katus et al., 2015a; Vogel & Machizawa, 2004).

254 Spline-interpolated voltage maps illustrate the topographical distribution of lateralized  
255 activity during the retention period (300 to 1000 ms). These maps were obtained by subtracting  
256 ipsilateral CSDs from contralateral CSDs, with contra-/ ipsilateral referring to the task-relevant  
257 side. To collapse data across blocks where the left or right side was task-relevant, electrode  
258 coordinates were flipped over the midline for left-side memory blocks. Therefore, in the  
259 topographical maps, a negative potential over the left hemisphere indicates the presence of  
260 contralateral delay activity for the task-relevant sample stimuli.

261

262 **Statistical analyses** Data were analyzed with paired t-tests and repeated-measures ANOVAs,  
263 with Greenhouse-Geisser adjustments when appropriate. Error bars in graphs indicate  
264 confidence intervals (CIs) for the true population mean. Thus, error bars that do not overlap  
265 with the zero axis ( $y \neq 0$ ) inform about statistically significant tCDA/CDA components; error  
266 bars that do not overlap with chance level ( $y \neq 50\%$ ) indicate behavioral performance that is  
267 significantly above chance.

268 Bayesian t-tests (Rouder et al., 2009) and the software Jasp (JASP team 2016) were  
269 used to calculate Bayes factors for each main effect / interaction in our statistical designs. The

270 Bayes factor denotes the relative evidence for the alternative hypothesis as compared to the  
271 null hypothesis, and thus allows for statistical inferences regarding the presence or absence of  
272 a modulation. The Bayes factor for the null-hypothesis ( $BF_{01}$ ) corresponds to the inverse of the  
273 Bayes factor for the alternative hypothesis ( $BF_{10}$ ), and indexes the relative evidence in the data  
274 that an effect is absent rather than present. We report the numerically larger BF; reliable  
275 evidence for either hypothesis is marked by a  $BF > 3$  (Jeffreys, 1961), suggesting that the  
276 empirical data is at least 3 times more likely under this hypothesis as compared with the  
277 competing hypothesis.

278

279

## 280 Results

281

282 **EEG data.** Tactile and visual CDA components (tCDA/CDA) entered an ANOVA with the  
283 factors *Component* (tCDA, CDA), *Tracked modality Load* (TL: tactile load for the tCDA, visual  
284 load for the CDA) and *Untracked modality Load* (UL: visual load for the tCDA, tactile load for  
285 the CDA). As observed previously (Katus et al., 2017), the CDA component was larger than  
286 the tCDA (*Component*:  $F(1,29) = 42.893$ ,  $p < 10^{-6}$ ,  $BF_{10} > 10^{32}$ ). Load manipulations in touch  
287 and vision selectively modulated the tCDA and CDA component, respectively (TL:  $F(1.344,$   
288  $38.973) = 23.238$ ,  $p < 10^{-5}$ ,  $BF_{10} > 10^6$ ). Critically, the tCDA was not sensitive to differences in  
289 visual load and the CDA was unaffected by the manipulation of tactile load (UL:  $F(2, 58) =$   
290  $0.141$ ,  $p = 0.727$ ,  $BF_{01} = 41.251$ ), and there was no interaction between load in the two  
291 modalities (TL x UL:  $F(3.001, 87.025) = 0.890$ ,  $p = 0.450$ ,  $BF_{01} = 48.282$ ). Load-dependent  
292 enhancements of CDA/tCDA amplitudes differed between touch and vision (*Component* x TL:

293  $F(2, 58) = 14.457, p < 10^{-5}, BF_{10} > 10^3$ ). This is illustrated in Figure 2, where the black line  
294 graphs on the bottom row show the impact of tactile load on the tCDA (left panel) and the  
295 influence of visual load on the CDA (right). Visual load parametrically enhanced the CDA  
296 (collapsed for tactile load, comparison 1 vs. 2 visual items:  $t(29) = 2.349, p = 0.026, BF_{10} =$   
297  $2.039$ ; 2 vs. 3 visual items:  $t(29) = 6.150, p < 10^{-5}, BF_{10} > 10^4$ ), with largest CDA amplitudes  
298 measured in trials with 3 visual items (cf. Vogel & Machizawa, 2004). In contrast, the tCDA  
299 reached asymptote for 2 tactile items (collapsed for visual load, 1 vs. 2 tactile items:  $t(29) =$   
300  $3.712, p < 10^{-3}, BF_{10} = 37.518$ ; comparison 2 vs. 3 items:  $t(29) = 1.215, p = 0.234, BF_{01} =$   
301  $2.635$ ). All remaining effects were non-significant (*Component* x UL:  $F(2, 58) = 0.996, p =$   
302  $0.375, BF_{01} = 14.497$ ; *Component* x TL x UL:  $F(4, 116) = 0.955, p = 0.435, BF_{01} = 18.427$ ).

303

304 -----

305 Insert Figure 2 here

306 -----

307

308

309 **Behavioral data** The percentage of correct responses entered an ANOVA with the factors  
310 *Tested modality* (touch, vision), *Tested modality Load* (TL: tactile or visual load, depending on  
311 whether memory was tested for touch or vision on a given trial) and *Untested modality Load*  
312 (UL: load for the other, untested, modality). Participants responded correctly in 79.4% and  
313 87.1% of trials where memory was tested for touch and vision, respectively, and this difference  
314 was significant (*Tested modality*:  $F(1, 29) = 21.583, p < 10^{-4}, BF_{10} > 10^{12}$ ). Most importantly, as

315 shown in Figure 3A, load manipulations caused strictly modality-specific effects. Performance  
316 decreased when load increased in the tested modality from 1 to 2 and 3 items (TL:  $F(2, 58) =$   
317  $226.533$ ,  $p < 10^{-20}$ ,  $BF_{10} > 10^{60}$ ). Critically, no such decrements were found as a result of  
318 increased load in the untested modality (UL:  $F(2, 58) = 1.883$ ,  $p = 0.161$ ,  $BF_{01} = 26.742$ ). All  
319 other effects were non-significant (TL x UL:  $F(4, 116) = 0.812$ ,  $p = 0.520$ ,  $BF_{01} = 68.807$ ;  
320 *Tested modality* x TL:  $F(2, 58) = 0.880$ ,  $p = 0.420$ ,  $BF_{01} = 10.223$ ; *Tested modality* x UL:  $F(2,$   
321  $58) = 1.321$ ,  $p = 0.275$ ,  $BF_{01} = 16.504$ ; *Tested modality* x TL x UL:  $F(3.081, 89.357) = 1.170$ ,  $p$   
322  $= 0.328$ ,  $BF_{01} = 17.315$ ).

323 To assess modality-specific capacity limits for visual and tactile WM in Experiment 1, we  
324 calculated Cowan's K (Cowan, 2001) for load-2 and load-4 in vision and touch (collapsing  
325 across load in the other untested modality). For visual WM, K values of 1.43 and 1.77 were  
326 obtained on load-2 and load-3 trials, and this difference was highly reliable ( $t(29) = 7.521$ ,  $p <$   
327  $10^{-7}$ ,  $BF_{01} > 10^5$ ). For tactile WM, K values of 1.13 and 1.23 were obtained on load-2 and load-  
328 3 trials. This increase was not significant ( $t(29) = 1.443$ ,  $p = 0.160$ ,  $BF_{01} = 2.022$ ), suggesting  
329 that in contrast to vision, the capacity of tactile WM was already exhausted with a load of 2  
330 items. For comparison, K-values increased significantly between load-1 and load-2 trials not  
331 only in vision (0.92 versus 1.43;  $t(29) = 9.644$ ,  $p < 10^{-9}$ ,  $BF_{01} > 10^6$ ), but also in touch (0.79  
332 versus 1.13;  $t(29) = 5.838$ ,  $p < 10^{-5}$ ,  $BF_{01} > 10^3$ ).

333

334 -----

335 Insert Figure 3 here

336 -----



337

## 338 **Experiment 2**

339           In Experiment 1, manipulations of visual and tactile WM load produced entirely  
340 modality-specific effects, and no crossmodal interference effects were found either for visual  
341 and tactile CDA components or for behavioral performance in the bimodal WM task. This  
342 pattern of results seems to suggest that WM capacity limitations are strictly modality-specific.  
343 However, alternative interpretations remain. The load manipulations used in Experiment 1 may  
344 not have been sufficiently high to produce crossmodal costs. Previous experiments where  
345 visual and auditory WM tasks were combined found no dual-task interference when auditory  
346 WM load was low (e.g., Morey & Cowan, 2004; Luck & Vogel, 1997), whereas such effects  
347 typically emerged with higher loads (e.g. Cocchini et al. 2002; Sauls & Cowan, 2007; but see  
348 Fougne et al., 2015, for an exception). Although the WM capacity estimates for vision and  
349 touch in Experiment 1 suggest that a maximal load of 3 items exhausted the capacity of visual  
350 and tactile stores, performance may have been affected by the specific demands of the  
351 lateralized WM task used in this experiment. For example, items that were located on the to-  
352 be-ignored side of the sample set could have interfered with the encoding of the task-relevant  
353 items in the same modality, resulting in an underestimation of WM capacity limitations.  
354 Participants may also have adopted specific strategies for reducing the effective loads of the  
355 visual and tactile WM tasks. In the visual task, some perceptual grouping of item locations may  
356 have occurred, especially for load-3. On load-3 trials in the tactile task, three of the four  
357 stimulators on the task-relevant hand were activated. In some of these trials, participants may  
358 have only memorized the single non-stimulated location, thereby reducing tactile load from 3 to  
359 1 on these trials.

360 Experiment 2 was designed to address all of these possible shortcomings of Experiment  
361 1. In this purely behavioral experiment, bilateral visual and tactile WM tasks were used where  
362 participants had to memorize all visual and tactile sample stimuli in both visual hemifields and  
363 both hands. Because all sample stimuli were now task-relevant, there was no longer any  
364 possibility of interference by to-be-ignored items of the sample set. In bimodal trials, visual and  
365 tactile load was varied independently (2 or 4 items). On tactile load-4 trials, two sample items  
366 were delivered to the left hand and two to the right hand, so that a strategy to only memorize a  
367 single non-stimulated location was no longer available. To eliminate potential grouping  
368 strategies for memorized visual positions in trials with high visual load, the spatial WM task  
369 was replaced with a color task for the visual modality. We employed the standard color change  
370 detection procedure introduced by Vogel & Luck (1997). Observers had to memorize two or  
371 four colors and to report whether one of these colors was changed in the test display.  
372 Importantly, Experiment 2 also included unimodal baseline trials where two or four visual or  
373 tactile items had to be memorized, in order to demonstrate that a unimodal load of 4 items was  
374 sufficient to exhaust the capacity of visual and tactile WM stores. If crossmodal interference  
375 effects emerge when the effective WM load within both modalities is sufficiently high, such  
376 effects should be observed in Experiment 2.

377

## 378 **Materials and methods**

379

380 **Participants.** 12 participants (average age: 28.8y, 7 female, 10 right-handed) were tested. All  
381 were neurologically unimpaired and gave informed written consent.

382

383 **Stimuli and procedure.** These were similar to Experiment 1, with the following exceptions. No  
384 EEG was recorded during task performance. The WM task was no longer lateralized, as visual  
385 and/or tactile sample stimuli on both sides were task-relevant. WM load was 2 or 4 items  
386 (separately varied for touch/vision), and unimodal visual and tactile baseline trials (load 2 or 4)  
387 were also included. The tactile task was similar to the one used in Experiment 1. Participants  
388 had to memorize the locations of all tactile sample stimuli that could be presented to the index,  
389 middle, ring, or little fingers of the left and right hand. The stimulated locations on each hand  
390 were chosen randomly and independently on each trial. In load-2 trials, one finger on each  
391 hand was stimulated. In load-4 trials, sample stimuli were delivered to two fingers of each  
392 hand. The tactile test set included two or four tactile stimuli in load-2 and load-4 trials,  
393 respectively. On match trials, the test set was identical to the memory set. On mismatch trials,  
394 one randomly selected sample location was replaced by a different location on the same hand.  
395 The visual task was now a bilateral color change detection task. Sample displays contained  
396 two or four differently colored squares (each covering  $0.52^\circ \times 0.52^\circ$  of visual angle). The colors  
397 shown on each trial were randomly selected from a set of six possible colors (CIE color  
398 coordinates for red: .627/.336; green: .263/.568; blue: .189/.193; yellow: .422/.468; cyan:  
399 .212/.350; magenta: .289/.168). All colors were equiluminant ( $11.8 \text{ cd/m}^2$ ). On load-2 trials, two  
400 sample squares were presented to the left and right of fixation at a horizontal eccentricity of  $1^\circ$ .  
401 On load-4 trials, two horizontally aligned squares were presented above and two below  
402 fixation, each at a horizontal and vertical eccentricity of  $1^\circ$ . Participants had to memorize the  
403 colors of all sample stimuli. On match trials, the test set was identical to the sample set. On  
404 mismatch trials, one item in the test set changed its color relative to the sample set.

405           The experiment included 480 trials, run in 8 blocks of 60 trials. There were 320 bimodal  
406 and 160 unimodal trials that were randomly intermixed in each block. For bimodal trials, visual  
407 and tactile load (2 or 4 item) was varied independently, resulting in four different load  
408 conditions. Memory was unpredictably tested for touch or vision (160 trials each, with 40 trials  
409 for each for the four load conditions). In the unimodal trials, the sample and test sets were  
410 presented in the same modality (80 tactile and 80 visual; with 40 trials each for load-2 and  
411 load-4). As in Experiment 1, vocal responses (“a” for match and “e” for mismatch) were  
412 registered with a headset microphone for each trial. The timing of all sample and test events  
413 was identical to Experiment 1.

414

415

## 416 **Results**

417           Figure 3B shows accuracy on trials where touch or vision was tested, for each  
418 combination of WM load in the tested modality (2 or 4 items) and load in the untested modality  
419 (0 items in the unimodal baseline, otherwise 2 or 4 items). There were clear effects of  
420 increasing WM load for the tested modality, but no apparent effects of load in the other  
421 untested modality. We first assessed whether increasing visual and tactile load to 4 items was  
422 sufficient to exhaust the capacity of visual and tactile WM by calculating Cowan’s K as a  
423 measure of WM capacity for the two single-task visual and tactile baseline conditions,  
424 separately for loads of 2 and 4 items. With load-2, K was 1.91 and 1.94 for the tactile and  
425 visual tasks, respectively, reflecting near-perfect performance. With load-4, K was 3.13 in the  
426 tactile task and 3.25 in the visual task. This indicates that a WM load of 4 items exhausted the  
427 capacity of both tactile and visual stores.

428 For the main analysis, accuracy entered an ANOVA with the factors *Tested modality*  
429 *Load* (TL: 2 or 4 items), *Untested modality Load* (UL: 0, 2 or 4 items) and *Tested Modality* (TM:  
430 vision or touch). This analysis confirmed the presence of strong modality-specific load effects  
431 in the absence of any crossmodal effects. Accuracy was lower when 4 rather than 2 items had  
432 to be memorized in the tested modality (TL,  $F(1,11) = 43.575$ ,  $p < 10^{-4}$ ,  $BF_{10} > 10^{15}$ ). In  
433 contrast, there was no impairment of WM performance due to load in the untested modality  
434 (UL:  $F(2, 22) = 1.333$ ,  $p = 0.284$ ,  $BF_{01} = 6.550$ ), and no interaction between load in the tested  
435 and untested modalities (TL x UL:  $F(2, 22) = 0.623$ ,  $p = 0.546$ ,  $BF_{01} = 7.339$ ).<sup>1</sup> Accuracy did  
436 not differ between the tactile and visual tasks (93.4% vs. 94.5%, averaged across all load  
437 conditions, main effect TM:  $F(1, 11) = 0.631$ ,  $p = 0.444$ ,  $BF_{01} = 2.220$ ). There were no other  
438 significant interactions (TM x TL:  $F(1, 11) = 0.095$ ,  $p = 0.763$ ,  $BF_{01} = 3.634$ ; TM x UL:  $F(2, 22) =$   
439  $0.677$ ,  $p = 0.518$ ,  $BF_{01} = 7.553$ ; TM x TL x UL:  $F(2, 22) = 0.648$ ,  $p = 0.533$ ,  $BF_{01} = 4.682$ ).

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441

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<sup>1</sup> To assess whether behavioral measures reflected a tradeoff between the number of tactile and visual items maintained in WM, we calculated  $\Delta K$  to obtain a normalized measure of any interference between the tactile and visual tasks. The  $\Delta K$  measure (Fougnie & Marois, 2011) quantifies dual-task interference relative to single-task baseline conditions in terms of a value ranging between 0% (reflecting fully independent WM capacities for two tasks/modalities) and 50% (fully shared WM capacity).  $\Delta K$  for trials where load was 4 in both modalities was on average 0.4% (relative to the unimodal 4-item baselines).  $\Delta K$  values were significantly below 50% ( $t(11) = 12.530$ ,  $p < 10^{-7}$ ,  $BF_{10} > 10^4$ ), but not different from 0% ( $t(11) = 0.112$ ,  $p = 0.913$ ,  $BF_{01} = 3.461$ ), indicating distinct rather than shared capacities for tactile and visual WM.

## 442 Discussion

443

444 We investigated whether the maintenance of information in WM is mediated by a domain-  
445 general (i.e., central/supramodal) mechanism or by processes that operate independently for  
446 WM content that has been encoded via different sensory modalities. In two experiments, we  
447 employed bimodal tactile-visual WM tasks, and manipulated WM load orthogonally for both  
448 modalities. In Experiment 1, spatial WM tasks were used in both modalities. EEG was  
449 recorded during task performance, and tactile and visual CDA components (tCDA/CDA) were  
450 measured to concurrently track the activation of tactile and visual WM representations.

451 If visual and tactile WM representations were maintained by a central mechanism,  
452 varying visual load should affect the somatosensory tCDA component, and changes in tactile  
453 load should modulate the visual CDA. There were no such crossmodal load effects in  
454 Experiment 1. CDA amplitudes were entirely unaffected by manipulations of tactile WM load,  
455 and tCDA amplitudes remained equally insensitive to manipulations of visual load. The  
456 reliability of these null-effects was confirmed by Bayesian statistics. Bayes factors (BFs, see  
457 Rouder et al., 2017) for each main effect and interaction in our factorial design (such as TL,  
458 UL, and TL x UL) quantify the relative evidence in the data for the null hypothesis (e.g., the  
459 absence of an effect of WM load in the untracked modality) as compared to the alternative  
460 hypothesis (the presence of such an effect). The BFs strongly support the null hypothesis with  
461 regards to load in the untracked modality (factor UL) and its interaction with load in the tracked  
462 modality (TL x UL), thus confirming the absence of crossmodal interference effects on the  
463 tCDA (due to visual load), and on the visual CDA (due to tactile load). Adopting a commonly  
464 used categorization of BF sizes (Jeffreys, 1961), we found *very strong* evidence for the

465 absence of tCDA/CDA modulations due to the factor UL ( $BF_{01} = 41$ ), as well as *very strong*  
466 evidence for the absence of an interaction between TL and UL ( $BF_{01} = 48$ ). For both these  
467 effects, the null hypothesis was over 40 times more likely to account for the empirical data than  
468 the alternative hypothesis. This electrophysiological evidence for the absence of crossmodal  
469 load effects is at least 4 times stronger than suggested by behavioral evidence, obtained in a  
470 recent auditory/visual WM experiment (Fougnie et al., 2015), where  $BF_{S01}$  ranged between 7  
471 and 10. It is notable that these highly reliable null-effects were accompanied by *decisive*  
472 evidence for an impact of factor TL ( $BF_{10} > 10^6$ ), indicating the presence of load-dependent  
473 tCDA/CDA modulations for manipulations of tactile/visual WM load, respectively. These results  
474 therefore unequivocally support the conclusion that the tactile and visual CDA components  
475 reflect WM maintenance processes that operate in a strictly modality-specific fashion.

476 This conclusion was further supported by the behavioral results of Experiment 1. For the  
477 modality assessed at memory test, increments in WM load led to parametric reductions in  
478 performance, but performance was insensitive to load in the untested modality (Fig. 3A).  
479 Converging with electrophysiological data, Bayesian analysis of behavioral performance  
480 provided *strong* to *very strong* evidence for the absence of crossmodal load effects ( $BF_{01} = 27$   
481 for factor UL and  $BF_{01} = 69$  for the TL x UL interaction), and *decisive* evidence for the  
482 presence of modulations due to increments in load for the modality that was tested after the  
483 trial ( $BF_{10} > 10^{60}$  for factor TL). It would in principle have been possible to observe crossmodal  
484 load effects for performance only, without any corresponding effects on CDA and tCDA  
485 components. Such a pattern of results would have suggested that crossmodal interference  
486 specifically affects stages other than WM maintenance, such as the comparison between  
487 memorized and test stimuli. In fact, the electrophysiological and behavioral results of

488 Experiment 1 mirrored each other perfectly, with no evidence for crossmodal load effects for  
489 either measure. This indicates that none of the stages involved in WM performance were  
490 selectively affected by concurrent WM load in another modality.

491 The fact that performance in Experiment 1 was better in the visual relative to the tactile  
492 task could indicate that participants had prioritized vision over touch. This should have  
493 produced asymmetrical crossmodal interference effects according to a domain-general  
494 account of WM capacity. For example, if visual stimuli had been preferentially encoded into a  
495 shared domain-general WM store, performance on trials where memory was tested for a tactile  
496 load of 3 items should be worse with visual load-3 relative to visual load-1. Because accuracy  
497 data from trials where vision or touch were tested were analyzed together, the presence of  
498 selective crossmodal costs for the low-priority (tactile) modality should have been reflected by  
499 a three-way interaction (Tested modality x TL x UL). As reported above, there was strong  
500 evidence for the absence of this interaction ( $BF_{01} > 17$ ). Likewise, we found strong evidence  
501 against asymmetrical crossmodal interference effects on tactile and visual CDA components  
502 (Component x TL x UL;  $BF_{01} > 18$ ). These observations suggest that performance differences  
503 between the tactile and visual tasks in Experiment 1 were not attributable to a modality  
504 prioritization strategy.

505 The ERP results of Experiment 1 revealed a difference between the effects of memory  
506 load in the tracked modality (TL) on CDA and tCDA components. Increasing visual load led to  
507 parametric amplitude enhancements of the CDA component over visual cortex, with largest  
508 CDA amplitudes on trials where 3 visual items had to be memorized, in line with previous  
509 experiments of unimodal visual WM (McCollough et al., 2007; Vogel & Machizawa, 2004). The  
510 tactile CDA (tCDA) component over somatosensory cortex increased in amplitude when tactile



511 load increased from 1 to 2 items (compare Katus et al., 2015a for unimodal tactile WM), but no  
512 further tCDA enhancement was obtained for 3 tactile items. This difference between the visual  
513 and tactile CDA components was mirrored by behavioral capacity estimates for visual and  
514 tactile WM. In vision, Cowan's K increased significantly when visual load was increased from 2  
515 to 3 items, whereas no such increase was observed for touch, indicating that in the specific  
516 task context of Experiment 1, the capacity limit of tactile WM was already reached with 2 items.  
517 The fact that tactile WM capacity was substantially higher in the non-lateralized WM task used  
518 in Experiment 2 shows that more than 2 tactile items can be successfully maintained in some  
519 conditions (see below for further discussion). It remains to be determined whether it is  
520 principally possible to obtain tCDA enhancements beyond a load of 2 tactile items in other task  
521 contexts. Importantly, any difference between CDA and tCDA asymptotes does not affect our  
522 key finding that the load-dependent modulations of CDA and tCDA amplitudes were strictly  
523 modality-specific, as demonstrated by the fact that these amplitudes remained entirely  
524 unaffected by manipulations of WM load in the other modality.

525 To rule out the possibility that the absence of crossmodal load effects was due to the  
526 specific task demands of Experiment 1, we ran a second behavioral experiment with a non-  
527 lateralized design where all sample stimuli were task-relevant. Visual and tactile load was 2 or  
528 4 items, the spatial WM task in the visual modality was replaced by a color change detection  
529 task, and unimodal baseline trials were included. The results of Experiment 2 fully confirmed  
530 the findings of Experiment 1, with strictly modality-specific load effects, and no evidence for  
531 any crossmodal interference. Capacity estimates on baseline trials confirmed that a load of 4  
532 items was sufficient to exhaust the capacity of visual and tactile stores. Furthermore, the  
533 design of Experiment 2 prevented participants from reducing effective WM load by grouping

534 locations in the visual task, or remembering non-stimulated locations in the tactile task. The  
535 fact that load effects remained entirely modality-specific in this experiment thus suggests that  
536 the analogous pattern observed in Experiment 1 was not due to insufficient demands on  
537 storage capacity, but instead reflects the independence of WM maintenance processes in  
538 different modalities.

539         It is notable that WM performance differed considerably between these two  
540 experiments, with much better performance in Experiment 2. This difference was particularly  
541 pronounced for the tactile WM task, in spite of the fact that participants had to memorize  
542 stimulated locations in both experiments. Even on tactile load-1 trials, accuracy was well below  
543 100% in Experiment 1. The improved tactile WM performance in Experiment 2 is most likely  
544 due to the fact that a non-lateralized WM task was used where all tactile sample stimuli on  
545 both hands to be memorized. In contrast to the lateralized task in Experiment 1, there was no  
546 longer any interference from stimulated locations on the other unattended hand, and the  
547 average distance between two tactile stimuli on the same hand was larger. The finding that  
548 approximately three tactile stimuli could be successfully retained on load-4 trials in Experiment  
549 2 demonstrates that under such optimal conditions, the capacity of tactile WM stores appears  
550 to be limited to three items. Visual WM accuracy was also better with the highly distinguishable  
551 color stimuli used in Experiment 2 relative to the spatial WM task with monochrome stimuli in  
552 Experiment 1. Previous research has shown that visual WM performance is affected by the  
553 features that have to be memorized, with tasks involving color typically yielding better  
554 performance than tasks where other stimulus dimensions have to be retained (e.g., orientation  
555 or shape; Awh et al. 2007; Alvarez & Cavanagh, 2004; Woodman & Vogel, 2008). In addition,  
556 some interference from stimuli in the unattended visual field may also have contributed to the

557 lower visual WM performance in Experiment 1. However, the behavioral estimate of WM  
558 capacity in Experiment 2 ( $K = 3.25$  items) is in line with the parametric load-dependent CDA  
559 enhancements observed in Experiment 1 (for up to 3 visual items).

560 What does the absence of crossmodal interference effects on performance in both  
561 experiments, and on CDA and tCDA amplitudes in Experiment 1, imply for the nature of  
562 mechanisms that control the storage of information in WM? It is established that WM and  
563 selective attention are closely intertwined (Awh & Jonides, 2001; Gazzaley & Nobre, 2012;  
564 Ruchkin, Grafman, Cameron, & Berndt, 2003), and that attentional mechanisms underpin the  
565 active maintenance of WM representations (e.g., Awh, Vogel, & Oh, 2006; Emrich, Lockhart, &  
566 Al-Aidroos, 2017). Attention optimizes WM representations in a goal-directed fashion (Lepsien  
567 & Nobre, 2006; Myers, Stokes, & Nobre, 2017), and the allocation of attention to task-relevant  
568 items in WM enhances performance (e.g., Griffin & Nobre, 2003). In line with these ideas,  
569 electrophysiological evidence suggests that lateralized delay activity (such as the tCDA/CDA)  
570 does not reflect information storage as such, but more specifically the attentional activation of  
571 representations of memorized stimuli in sensory cortex (e.g., Berggren & Eimer, 2016; Katus  
572 & Eimer, 2015; Kuo, Stokes, & Nobre, 2012). This is analogous to the early interpretation of  
573 delay activity in the prefrontal cortex of monkeys as the indication of a top-down attentive  
574 process (Fuster & Alexander, 1971). While passive mechanisms may also be involved in the  
575 short-term storage of information (Mongillo, Barak, & Tsodyks, 2008; for a review of “activity-  
576 silent WM”, see Stokes, 2015), CDA/tCDA components reflect activation-related aspects of  
577 WM maintenance that are mediated by selective attention (Unsworth, Fukuda, Awh, & Vogel,  
578 2015; Vogel, McCollough, & Machizawa, 2005; Katus & Eimer, 2015; Katus & Müller, 2016). If  
579 these active maintenance processes were limited by the capacity of a central attention

580 mechanism (Cowan, 2011), they should be adversely affected by increasing WM load in  
581 another modality, provided that this results in an overall bimodal WM load exceeds the  
582 capacity of this domain-general mechanism. However, the present study found that increasing  
583 multisensory load above the 3-4 item capacity limit of unimodal WM (Cowan, 2001; Vogel  
584 & Machizawa, 2004) did not produce any crossmodal interference effects for CDA and tCDA  
585 amplitudes. The absence of such effects suggests that the maintenance processes indexed by  
586 the tCDA/CDA components are mediated by modality-specific attention mechanisms with  
587 independent capacities for tactile and visual information that are activated in parallel during the  
588 maintenance of multisensory information.

589         Such modality-specific attentional control processes operate within hierarchically  
590 organized WM systems (Brady, Konkle, & Alvarez, 2011), which are controlled in a top-down  
591 fashion by higher-level executive mechanisms (e.g., Katus et al., 2017). This distributed nature  
592 of WM (Christophel, Klink, Spitzer, Roelfsema, & Haynes, 2017; Fuster, 2009) can account for  
593 the fact that the capacity of multisensory WM (i.e., the number of multisensory items that can  
594 be recalled at memory test) exceeds the capacity of unimodal WM (Cowan et al., 2014;  
595 Fougne et al., 2015; Fougne & Marois, 2011). In such a distributed processes architecture,  
596 capacity limitations can arise due to the competition between stimulus representations that are  
597 stored in the same cortical map (in somatosensory vs. retinotopic cortex, for tactile vs. visual  
598 information; cf. “cortical real estate” hypothesis: Bergmann et al., 2016; Franconeri, Alvarez, &  
599 Cavanagh, 2013), and due to capacity limitations of the maintenance processes that keep  
600 these sensory representations in an active state (as indexed by the tCDA/CDA in tactile/visual  
601 WM tasks). Instead of assuming that multisensory items compete for representation in a  
602 central WM store, and/or for domain-unspecific attention resources (Cowan, 2011; Saults

603 & Cowan, 2007), crossmodal interference effects observed in bimodal WM tasks are likely to  
604 reflect factors that are unrelated to WM capacity (e.g., costs that arise during dual-task  
605 coordination, or during the simultaneous encoding of multisensory stimuli, response selection,  
606 etc.: Brisson & Jolicoeur, 2007; Cocchini et al., 2002; Fougny et al., 2015 for further  
607 discussion). Competitive interactions between modality-specific maintenance processes may  
608 also contribute to such costs, given that these processes rely on feedback signals from a  
609 common source (such as a central executive; Baddeley, 2003). This is most likely to happen in  
610 bimodal WM tasks with extremely high load (e.g., 10 multisensory items, as in Cowan et al.,  
611 2014), as such tasks may compromise the ability of the central executive system to effectively  
612 coordinate and sustain concurrent activation processes within different sensory modalities (cf.  
613 Tamber-Rosenau & Marois, 2016).

614

615 **Conclusion** Building on evidence that WM recruits sensory mechanisms for information  
616 storage, we here show that WM additionally recruits modality-specific control mechanisms to  
617 regulate the activation of stimulus representations in somatosensory and visual cortex. The  
618 parallel functioning of such distributed processes during the retention of multisensory  
619 information explains the absence of crossmodal load effects on behavioral and  
620 electrophysiological measures of WM, and can also account for the enhanced capacity of  
621 multisensory WM relative to unimodal WM.

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633

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## 774 **Figure legends**

775 **Figure 1. Multisensory memory task for locations in Experiment 1.** Simultaneously  
776 presented tactile and visual sample sets (duration 200 ms) were followed by a unimodal –  
777 tactile or visual – test set after 1 second. Participants memorized the locations of the tactile  
778 and visual samples on the same side (left or right, varied block-wise) and judged whether any  
779 of these memorized locations matched with the memory test (50% match/mismatch, separately  
780 randomized for the attended/ignored sides). WM load (1, 2 or 3 items) alternated unpredictably  
781 across trials, and independently for the tactile and visual sample sets. The graph delineates a  
782 trial with visual load-3 and tactile load-2. The dots on the monitor represent the locations of the  
783 visual stimuli, and dots on the hands indicate the fingers that received tactile samples.

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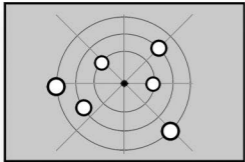
785 **Figure 2. EEG data in Experiment 1. (A)** Separate rows display tCDA difference waves,  
786 measured over somatosensory cortical regions, during the retention delay of tactile load-1,  
787 load-2 and load-3 trials. Line color indicates WM load in the visual modality (blue, yellow and  
788 red, for 1, 2 or 3 visual items). Statistical analyses were performed on the average of tCDA

789 amplitudes between 300 and 1000 ms, which are displayed for all tactile/visual load  
790 combinations in the bottom right panel. The left panel and the topographies show the impact of  
791 tactile load on data that were collapsed across the visual load conditions. **(B)** CDA difference  
792 waves, measured over visual cortical regions, as a function of visual load (separate rows) and  
793 tactile load (different colors). Mean CDA amplitudes for all tactile/visual load combinations are  
794 displayed in the fourth row, right panel. The left panel and the topographies illustrate CDA  
795 amplitudes, collapsed across the tactile load conditions. Note the different scales for the  
796 tCDA/CDA in (A) and (B); negative is plotted downwards.

797

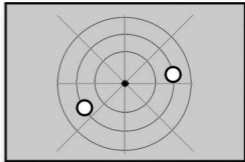
798 **Figure 3. Behavioral results in Experiment 1 (A) and Experiment 2 (B).** Performance (%  
799 correct) in trials where memory was tested for touch, for vision, and collapsed across both  
800 modalities, is plotted against WM load in the untested modality. In both experiments,  
801 performance decreased only when load increased for the tested modality (compare the  
802 different line types), but not for load increments in the untested modality (x-axis).

803



**Samples** Vision and Touch

50%  
↗



50%  
↘  
**Test** Vision or Touch

