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2 **Shifts of spatial attention in visual and tactile working memory are**
3 **controlled by independent modality-specific mechanisms**

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16

17

18 **Keywords**

19 • Electroencephalography (EEG), event-related potentials (ERPs)

20 • Multisensory (tactile / visual)

21 • Spatial attention

22 • Working memory (WM)

23 **Abstract**

24 The question whether the attentional control of working memory (WM) is shared
25 across sensory modalities remains controversial. Here, we investigated whether
26 attention shifts in visual and tactile WM are regulated independently. Participants
27 memorized visual and tactile targets in a first memory sample set (S1) before encoding
28 targets in a second sample set (S2). Importantly, visual or tactile S2 targets could
29 appear on the same side as the corresponding S1 targets, or on opposite sides, thus
30 requiring shifts of spatial attention in visual or tactile WM. The activation of WM
31 representations in modality-specific visual and somatosensory areas was tracked by
32 recording visual and tactile contralateral delay activity (CDA/tCDA). CDA/tCDA
33 components emerged contralateral to the side of visual or tactile S1 targets, and
34 reversed polarity when S2 targets in the same modality appeared on the opposite side.
35 Critically, the visual CDA was unaffected by the presence versus absence of
36 concurrent attention shifts in tactile WM, and the tactile CDA remained insensitive to
37 visual attention shifts. Visual and tactile WM performance was also not modulated by
38 attention shifts in the other modality. These results show that the dynamic control of
39 visual and tactile WM activation processes operates in an independent modality-
40 specific fashion.

41

42

43 **Introduction**

44 Working memory (WM) refers to the set of cognitive and neural mechanisms
45 that are responsible for the maintenance of perceptual information that is no longer
46 physically present, and for making this information accessible to other psychological

47 processes. Several lines of evidence point towards a critical role of spatial attention
48 during the encoding and storage of sensory signals in WM (Awh, Vogel, Oh 2006).
49 WM maintenance relies on frontoparietal networks that are also involved in the control
50 of spatial attention (Awh and Jonides 2001). The sustained activity of neurons in
51 prefrontal cortex that is observed during the delay period of WM tasks is selectively
52 tuned to memorized object locations on the contralateral side (Funahashi 2013). The
53 role of spatial attention for feature binding and the formation of object-based
54 representations in WM has been demonstrated by space-based competition effects
55 (Robertson 2003). For example, decreasing the spatial distance between competing
56 stimuli reduces WM precision and increases binding errors in WM (Emrich and Ferber
57 2012; Ahmad et al. 2017).

58 Electrophysiological studies of WM have provided additional evidence for links
59 between WM maintenance and space-based attentional control processes. Spatial
60 location appears to be represented in an obligatory fashion in visual WM, even when
61 it is task-irrelevant (Foster et al. 2017; Kuo et al. 2009; Katus, Andersen, Müller 2012).
62 The maintenance of sensory signals in WM during the delay periods of lateralized
63 visual and tactile change detection tasks is associated with spatially selective
64 modulations of event-related potentials (ERPs). Visual WM maintenance gives rise to
65 a sustained negativity contralateral to the to-be-memorized visual objects (Vogel and
66 Machizawa 2004), and an analogous contralateral negativity has also been found in
67 tactile WM tasks (Katus, Grubert, Eimer 2015). This visual contralateral delay activity
68 (CDA) and its tactile equivalent (tCDA component) have modality-specific
69 topographies over visual and somatosensory cortex, respectively. They reflect
70 spatially selective modulations of neural activity in modality-specific sensory-
71 perceptual cortical areas, in line with the sensory recruitment account of WM (Postle

72 2006). The fact that CDA and tCDA amplitudes both increase with the number of visual
73 or tactile stimuli that have to be maintained, and the fact that both are sensitive to
74 individual differences in WM capacity (Vogel and Machizawa 2004; Katus, Grubert,
75 Eimer 2015) demonstrate that these two components are linked to WM maintenance
76 processes in vision and touch.

77 Evidence that CDA components do not reflect the generic storage of content in
78 WM, but more specifically the attentional activation of WM representations comes from
79 studies that used retro-cue and sequential loading procedures (see also McElree,
80 2001; Oberauer and Hein, 2012, for discussions of links between attention and WM
81 storage). In retro-cue experiments, observers initially encode stimuli on both sides,
82 before a cue indicates the task-relevant items for the current trial. Retro-cues trigger
83 shifts of attention towards representations that are already stored in WM. These
84 attention shifts were found to modulate the CDA and tCDA components in visual
85 (Eimer and Kiss 2010) and tactile (Katus, Müller, Eimer 2015) retro-cue experiments.
86 In sequential loading tasks, participants memorize task-relevant target stimuli in two
87 sequentially presented sample sets (S1, S2). When the target items in S1 and S2 are
88 presented on opposite sides, CDA components are initially triggered contralateral to
89 the S1 targets, but then reverse polarity during the S2-period, reflecting the task-
90 relevant item locations in the second sample set. This polarity reversal was observed
91 for the tCDA in a tactile WM experiment (Katus and Eimer 2015) and for the CDA
92 during the sequential loading of visual WM (Berggren and Eimer 2016), indicating
93 shifts of spatial attention towards the contralateral side of somatotopic or retinotopic
94 space during the S2-period (see also Drew et al., 2014b, for an analogous polarity
95 reversal of visual CDA components during continuous object tracking when visual
96 objects cross the vertical midline). Importantly, even though visual and tactile CDA

97 components were elicited contralateral to S2 sample items on opposite-side trials in
98 these studies, memory performance for S1 items was still well above chance,
99 indicating that information about S1 was retained in WM, although presumably in a
100 different attention-independent format (see also Lewis-Peacock et al. 2012; LaRocque
101 et al. 2013; for additional fMRI and EEG evidence for activity-silent WM storage
102 mechanisms).

103 If top-down spatial attention modulates the storage of sensory stimuli in WM,
104 the important question arises how these attentional control processes operate in
105 multisensory WM tasks where items from different modalities have to be encoded and
106 maintained simultaneously. It has been argued that WM maintenance processes in
107 such multisensory tasks rely on modality-unspecific central attentional resources
108 (Cowan 2011). If this is correct, the ability to retain multiple stimuli from different
109 modalities in WM should be strongly affected by the spatial correspondence of these
110 stimuli. For example, visual and tactile sample stimuli should be maintained better
111 when they are presented on the same side than when they appear on opposite sides.
112 In the latter case, attention would have to be allocated to opposite sides in different
113 modalities, which will be difficult if these attention shifts are mediated by a single
114 modality-unspecific control system. Evidence for strong spatial synergies between
115 attentional control processes in vision, audition, and touch have indeed been identified
116 in previous behavioral and electrophysiological experiments on crossmodal links in
117 spatial attention (Spence and Driver 1996; Eimer, van Velzen, Driver 2002),
118 suggesting that attention shifts in different modalities are either closely linked or
119 controlled by shared central mechanisms.

120 Previous studies of multimodal WM have found performance costs in bimodal
121 WM tasks relative to unimodal baseline conditions (e.g., Cowan, Saults, Blume 2014;

122 Fougnie and Marois 2011; Saults and Cowan 2007), suggesting that some aspect of
123 WM processing in a given modality is impaired when items in another modality have
124 to be simultaneously maintained. If these bimodal costs were associated with the need
125 to coordinate shared spatially selective attentional control processes across sensory
126 modalities, they should be particularly pronounced under conditions where to-be-
127 memorized items in different modalities are presented at spatially incongruent
128 locations. Such spatial congruency effects on multimodal WM performance have not
129 yet been investigated systematically. One exception is a recent ERP study from our
130 lab (Katus and Eimer 2016) where participants memorized two tactile and two visual
131 sample stimuli that were either presented on the same side or on opposite sides. In
132 same-side blocks, visual and tactile CDA components were elicited over the same
133 hemisphere, each with their typical modality-specific topography. In opposite-side
134 blocks, these components emerged over different hemispheres, contralateral to the
135 respective task-relevant visual and tactile sample items. Critically, visual and tactile
136 CDAs were elicited at the same time and were identical in amplitude in same-side and
137 opposite-side blocks, and WM performance did not differ between these two types of
138 blocks. The absence of any behavioral or electrophysiological evidence for impaired
139 visual and tactile WM maintenance processes in the opposite-side blocks of this
140 experiment suggests that these processes are controlled by parallel and entirely
141 independent modality-specific mechanism of spatial attention.

142 The apparent independence of space-based attentional control processes
143 during visual and tactile WM maintenance suggested by the results of this previous
144 EEG experiment (Katus and Eimer 2016) contrasts with previous evidence for
145 crossmodal synergies in spatial attention (Eimer and van Velzen 2002; Spence and
146 Driver 1996; Eimer, van Velzen, Driver 2002), and is also inconsistent with claims that

147 WM storage in multisensory tasks is based on shared central control mechanisms
148 (Cowan 2011). It is possible that these results are specific to the particular task
149 conditions that were realized in this experiment. The fact that the side of task-relevant
150 visual and tactile sample items was specified in advance and remained constant for
151 an entire block enabled participants to activate constant attentional task sets for the
152 relevant visual and tactile locations prior to the start of each block. Furthermore,
153 because all sample stimuli were presented simultaneously, no dynamic re-allocations
154 of spatial attention between WM representations were required in this experiment.
155 These two factors may have been responsible for the absence of any evidence of
156 impaired WM maintenance in the opposite-side blocks of our previous CDA study
157 (Katus and Eimer 2016). Spatial synergies in the attentional control of WM
158 maintenance in bimodal tasks may emerge primarily under conditions where the
159 locations of task-relevant memory sample items vary unpredictably across trials, and
160 where attention has to shift rapidly between WM representations within and across
161 sensory modalities. This was tested in the present study.

162 We employed sequential loading procedures in bimodal visual/tactile WM
163 tasks. At the start of each trial, bimodal sample sets (S1) were presented, which were
164 followed after a delay period by a second sample set (S2), and then, after another
165 delay period, by a memory test display (vision or touch). The identity of the to-be-
166 memorized visual sample items was indicated by their shape (Experiment 1) or color
167 (Experiment 2), and task-relevant tactile items were defined by stimulus waveform
168 (pulsed versus continuous; in Experiments 1b and 2). These relevant visual and tactile
169 items (targets) were always accompanied by task-irrelevant items on the opposite side
170 of the sample sets. The critical manipulation concerned the need to shift attention in
171 either touch or vision in the period following S2. Tactile or visual S2 target items were

172 presented either on the same side or on the opposite side as the S1 targets in the
173 same modality. To track the activation of visual and tactile WM representations, we
174 measured CDA and tCDA components during the periods following S1 and S2.

175 In Experiment 1, the sequential loading task was performed for one primary
176 modality (vision in Experiment 1a, touch in Experiment 1b) and a secondary modality
177 (touch or vision in Experiments 1a and 1b, respectively). S1 always contained items
178 in both modalities, and task-relevant visual and tactile items were always presented
179 on the same side. S2 only contained primary-modality items, and the to-be-memorized
180 targets appeared unpredictably either on the same side as the target items in S1 or on
181 the opposite side (stay/shift trials; see Figure 1). Participants were instructed to
182 memorize the primary-modality target items in S1 and S2, while also maintaining the
183 secondary-modality S1 targets across both delay periods. Memory was unpredictably
184 tested for either modality. For vision, participants reported the presence/absence of a
185 color change between task-relevant visual sample and test stimuli. For touch, the
186 presence/absence of a location change had to be reported. In addition to these
187 bimodal task blocks, there were also unimodal baseline blocks where stimulus
188 presentation procedures were identical but WM was always tested for the primary
189 modality, so that S1 items for the secondary modality could be entirely ignored.

190 In unimodal blocks, reliable CDA components should only be elicited in the
191 currently task-relevant primary modality, but should not be present over sensory areas
192 for the secondary irrelevant modality. Visual and tactile CDA components for the
193 primary modality were expected to change polarity on switch trials but not on stay
194 trials, reflecting the dynamic re-allocation of spatial attention in response to S2 (Katus
195 and Eimer 2015; Berggren and Eimer 2016). If WM maintenance in vision and touch
196 relies on shared space-based attentional control mechanisms, spatial synergies

197 between visual and tactile WM should result in crossmodal interference effects from
198 vision to touch, and vice versa, on shift trials. This spatial interference should result in
199 general costs for WM performance on shift as compared to stay trials, and also affect
200 visual and tactile CDA components. For the primary modality, the requirement to
201 maintain a constant attentional focus in the other (secondary) modality should
202 attenuate or eliminate the CDA polarity reversal in response to S2 on shift trials,
203 relative to unimodal baseline blocks. For the secondary modality, the need to shift
204 versus maintain the attentional focus in the other (primary) modality should affect
205 visual or tactile CDA components in the interval following S2. The alternative possibility
206 is that top-down spatial attention operates in a strictly independent modality-specific
207 fashion within visual and tactile WM, even under conditions where attention has to be
208 rapidly re-allocated between WM representations. In this case, there should be no
209 spatial synergies between attentional control processes in vision and touch, no
210 crossmodal interference effects on WM performance on bimodal shift trials, and
211 critically, no differences between shift and stay trials for visual and tactile CDA
212 components. Bayesian statistics (Rouder et al. 2017) were employed to confirm the
213 reliability of any such null-effects.

214 In Experiment 2, S1 and S2 both contained target items from both modalities.
215 As in Experiment 1, the task-relevant tactile and visual items in S1 always appeared
216 on the same side. The location where visual and tactile target items in S2 were
217 presented (same versus side as in S1) was varied randomly and orthogonally,
218 resulting in four different trial conditions (both stay; both switch; vision stay/tactile
219 switch; vision switch/tactile stay). In this experiment, memory was tested for locations
220 in both vision and touch.

221

222 **Materials and methods**

223

224 **Participants**

225

226 All participants were neurologically unimpaired and gave informed written consent
227 prior to testing. 49 paid volunteers participated in the three experiments. 5 participants
228 were excluded from statistical analysis due to excessive EEG artifacts (1 participant
229 each in Experiments 1a and 1b, 3 participants in Experiment 2), resulting in a final
230 sample of 44 participants (Experiment 1a: 12 participants, 30y mean age, 7 female,
231 10 right-handed; Experiment 1b: 16 participants, 29y mean age, 11 female, 13 right-
232 handed; Experiment 2: 16 participants, 30y mean age, 10 female, 14 right-handed).
233 All experiments were conducted in accordance with the Declaration of Helsinki, and
234 were approved by the Psychology Ethics Committee, Birkbeck, University of London.

235

236 **Stimulus material and apparatus**

237 Visual stimuli were shown for 200 ms against a dark background on a 22 inch monitor
238 (Samsung wide SyncMaster 2233; 1280 x 1024 resolution, 100 Hz refresh rate, 16 ms
239 response time) at a viewing distance of 100 cm. Tactile stimuli were presented for
240 200 ms by eight mechanical stimulators on the left and right hands' distal phalanges
241 of the index, middle, ring and small fingers. The stimulators were driven by custom-
242 built amplifiers, using an eight-channel sound card (M-Audio, Delta 1010LT) controlled
243 by Matlab routines (MathWorks, Natick, MA). Continuous pink noise was played on
244 headphones to mask any sounds produced by the tactile stimulators. A headset
245 microphone recorded vocal responses in the 1800 ms response period after each trial
246 ('a' for match, 'e' for mismatch; details below).

247

248 **Task design**249 **Experiment 1a.** Vision and touch were primary and secondary modality, respectively.

250 The first bimodal memory sample set (S1, load: 2 visual and 2 tactile targets) was

251 followed by a second unimodal visual sample set (S2, load: 2 visual targets), and a

252 unimodal memory test stimulus set (50% tactile or visual in bimodal blocks, 100%

253 visual in unimodal blocks). The three sets were separated by intervals of 1000 ms.

254 Each visual sample set included two squares on one monitor side and two circles on

255 the other side (size: 0.63° of visual angle each). The side where a particular shape

256 appeared was independently randomized for S1 and S2. On stay trials (50%), the

257 shapes' locations did not change across S1 and S2. On shift trials (50%), shapes

258 locations were swapped (i.e., squares were followed by circles on one monitor side,

259 and circles were followed by squares on the other side); see Figure 1A. The shape

260 that defined the task-relevant visual sample stimuli (targets: circle or square) was

261 counterbalanced across participants, who memorized the targets' colors for both S1

262 and S2. For the four task-relevant target shapes in the S1 and S2 displays, four out of

263 six possible colors were selected on each trial (CIE color coordinates: red = $.627/.336$;264 green = $.263/.568$; blue = $.189/.193$; yellow = $.422/.468$; cyan = $.212/.350$; magenta =265 $.289/.168$). The four colors of the four task-irrelevant shapes in these displays were

266 selected independently from this set of six colors. Visual sample item pairs were

267 shown bilaterally in invisible 2-by-2 matrices (vertical eccentricity relative to stimulus

268 center: 0.46° of visual angle; horizontal eccentricity: 1.60° inner quadrants, 2.58° outer

269 quadrants). The sample pair on the left appeared in the top left and bottom right

270 locations, and the pair on the right in the top right and bottom left locations, or vice

271 versa. The task-relevant samples in S1 and S2 were always presented at different

272 locations, so that four colors at four different locations had to be memorized after S2;
273 see Figure 1. Visual test sets involved four target shapes in a 2-by-2 matrix at central
274 fixation (0.46° horizontal and vertical eccentricity). On visual match trials (50%), the
275 four memorized target colors were repeated. Their spatial arrangement (top/bottom,
276 left/right) matched the location of the memorized colors in the S1 and S2 displays. On
277 visual mismatch trials (50%), the color one of the four test display items was replaced
278 by a different not-memorized color.

279 Four identical tactile sample stimuli (100 Hz vibrations, intensity: 0.37 N) were
280 presented to two randomly selected fingers on the left and right hand, simultaneously
281 with the visual S1 displays. In bimodal blocks, participants were instructed to
282 memorize the locations of the tactile samples on the same side where the task-
283 relevant visual S1 sample shapes were presented. On half of all trials, pairs of tactile
284 stimuli were presented to the left and right hand at memory test. On tactile match trials
285 (50%), the two tactile test items on the task-relevant hand appeared at the same
286 locations as in S1. On tactile mismatch trials (50%), one of these two stimuli appeared
287 at a different location. The tactile locations on the other task-irrelevant hand were
288 selected in the same way for each tactile test set (50% match and mismatch trials for
289 S1 items presented to the irrelevant hand). Matches and mismatches on the attended
290 and unattended hands were uncorrelated. In unimodal blocks, only visual memory test
291 displays were presented, and participants could therefore ignore the tactile stimuli that
292 appeared concurrently with visual S1 displays. Experiment 1a included 12 blocks with
293 48 trials per block (576 trials in total, 144 trials for each of the four combinations of
294 stay/shift trials and unimodal/bimodal blocks). The unimodal and bimodal WM tasks
295 were performed in six successive blocks, with task order counterbalanced across
296 participants.

297 -----

298 insert Figure 1 about here

299 -----

300

301 **Experiment 1b** Touch was the primary modality, vision was the secondary modality.
302 Tactile targets were defined by stimulus waveform (counterbalanced across
303 participants, continuous: 200 ms vibration, or pulsed: two 10 ms pulses followed by
304 two 10 ms pulses after a 160 ms gap). Two tactile sample sets (S1 and S2) were
305 presented on each trial. S1 included two tactile stimuli (one continuous, one pulsed),
306 each delivered to a randomly selected finger of each hand. At S2, two different fingers
307 of each hand were stimulated. One hand received a pair of pulsed stimuli, the other a
308 pair of continuous stimuli). In stay trials, all continuous and all pulsed tactile S1 and
309 S2 stimuli were presented to the same hand. In shift trials, continuous and pulsed
310 stimuli swapped sides between S1 and S2, so that the to-be-memorized tactile stimuli
311 were presented to opposite hands. Bilateral visual sample stimuli (identical to
312 Experiment 1a) were presented simultaneously with the tactile S1 sets. No visual
313 samples appeared at S2. In bimodal blocks, participants memorized all tactile S1 and
314 S2 targets, as well as the visual S1 stimuli that were located on the same side as the
315 tactile S1 targets. Memory was unpredictably tested for touch or vision. Visual memory
316 test sets were identical to the sample sets, except that on mismatch trials (50%), one
317 of the sample colors on the task-relevant side was replaced by a different color. Tactile
318 memory test sets included one continuous and one pulsed stimulus, delivered to
319 different hands. Participants had to decide whether the location of the task-relevant
320 (continuous or pulsed) tactile test stimulus matched the location of one of the three

321 task-relevant tactile sample stimuli (match trials, 50%) or was presented at a different
322 location (mismatch trials, 50%). In unimodal blocks, only touch was tested, and visual
323 S1 stimuli could be ignored.

324 Experiment 1b included 12 blocks with 48 trials per block (576 trials in total, 144
325 trials for each of the four combinations of stay/shift trials and unimodal/bimodal
326 blocks). The unimodal and bimodal WM tasks were performed in six successive
327 blocks, counterbalanced across participants. Two procedural changes relative to
328 Experiment 1a were introduced for pragmatic reasons. First, participants memorized
329 two visual targets at S1 and S2, while in Experiment 1b, they had to memorize one
330 tactile S1 and two tactile S2 targets. This was necessitated by the fact that there were
331 only four tactile stimulus locations for each hand, and that a tactile WM load of two
332 items for S1 and S2 would have resulted in all four fingers of the same hand receiving
333 a target stimulus on stay trials. Second, the locations of visual S1 targets varied
334 unpredictably across trials in Experiment 1a, whereas the location of tactile S1 targets
335 (and thus the location of visual targets in bimodal blocks) remained constant in each
336 block in Experiment 1b, and was changed every three blocks (with the task-relevant
337 side for the first block having been randomly determined per participant). This was
338 done because pilot data indicated that a trial-wise randomization of tactile S1 target
339 locations would have resulted in an extremely challenging task. Critically for the
340 purposes of the present study, the location of tactile S2 targets (same versus opposite
341 side) remained entirely unpredictable.

342

343 **Experiment 2**

344 Participants concurrently performed sequential loading tasks in both modalities,
345 with bimodal S1 and S2 sets followed unpredictably by a unimodal tactile or visual test
346 set. As in Experiment 1b, the task-relevant tactile and visual S1 targets were located
347 on the same side (left or right), and this location remained constant within each block,
348 and was changed every three blocks. Critically, the locations of the task-relevant visual
349 and tactile sample stimuli in S2 were orthogonally randomized for each modality (stay
350 vs. shift, 50%), resulting in the need to shift attention in the period after S2 in neither
351 modality (25%), in only one modality (touch or vision, 25% each), or in both modalities
352 simultaneously (25%). In contrast to Experiment 1, where participants had to retain
353 the colors of visual samples and the locations of tactile samples, they memorized
354 stimulus locations for both modalities in Experiment 2. This change was introduced
355 because a common representational format for stimuli in different modalities has been
356 reported to produce crossmodal interference in previous auditory-visual WM tasks
357 (see Exp. 8 in Fougny et al. 2015).

358 Each visual sample set included pairs of two green and two red circles (stimulus
359 size: 0.40° of visual angle) on opposite sides. These stimuli were presented on two
360 virtual (invisible) concentric rings around the fixation dot (radius relative to fixation:
361 1.86° and 1.29° for the outer and inner rings). All four stimuli in each sample display
362 appeared at the same eccentricity. On trials where S1 items were located in the inner
363 ring, S2 items were located on the outer ring, or vice versa; see Figure 1. Stimulus
364 locations were randomly sampled from 140 angular positions (in polar coordinates:
365 110° to 250° for the left side, 290° to 70° for the right side) with the constraint that the
366 stimulus pairs on each side of the sample displays were separated by a minimum
367 distance of 80° . To-be-memorized visual target stimuli were defined by their color
368 (green or red, counterbalanced across participants). Participants now had to memorize

369 the locations of the task-relevant visual sample stimuli in S1 and 2. Visual memory test
370 displays contained one green and one red circle on opposite sides. Participants had
371 to decide whether the location of the target-color test item matched the location of one
372 of the visual target items in S1 and S2. This was the case in half of all trials where
373 visual WM was tested. In the remaining 50% mismatch trials, the target-color item in
374 the test display appeared at a different location, at an angular distance of 40° relative
375 one of the memorized locations in S1 or S2.

376 Tactile sample and test stimuli were identical to those used in Experiment 1b
377 (tactile targets: continuous or pulsed, counterbalanced across participants), with the
378 exception that only a single task-relevant tactile item was presented both at S1 and
379 S2. Each tactile sample set included a target and a distractor stimulus, presented to
380 opposite hands. S2 samples were never presented to any location stimulated at S1.
381 The task-relevant tactile stimulus in the test set either matched the location of one of
382 the two tactile targets in S1 or S2, or was presented to a non-target location (50%
383 match/mismatch). Experiment 2 included 16 blocks with 34 trials per block (544 trials
384 in total; 136 trials for each of the four combinations of tactile stay/shift and visual
385 stay/shift trials). The task-relevant side for S1 was randomly determined for block 1,
386 and changed to the opposite side in block 9.

387

388 **Analysis of EEG data**

389 **Acquisition and pre-processing** EEG data, sampled at 500 Hz using a BrainVision
390 amplifier, were DC-recorded from 64 Ag/AgCl active electrodes at standard locations
391 of the extended 10-20 system. Two electrodes at the outer canthi of the eyes
392 monitored horizontal eye movements (horizontal electrooculogram, HEOG).

393 Continuous EEG data were referenced to the left mastoid during recording, and re-
394 referenced to the arithmetic mean of both mastoids for data pre-processing. Data were
395 offline low-pass filtered (20 Hz, Blackman window, filter order 1000). All EEG results
396 reported below were virtually identical when a higher low-pass cut-off of 40 Hz was
397 employed. Epochs were extracted for the 2s period after the sample set, and were
398 corrected relative to a 200 ms pre-stimulus baseline.

399

400 **Artefact rejection and correction** We first rejected trials with saccades using a
401 differential step function that ran on the bipolarized HEOG (step width 100 ms,
402 threshold 30 μV) prior to artefact correction. *Independent Component Analysis* (ICA)
403 (Delorme, Sejnowski, Makeig 2007) was employed to correct for frontal artefacts such
404 as eye blinks, and residual traces of horizontal eye movements that had not been
405 detected by the step function. We further rejected trials in which difference values for
406 corresponding left- minus right-hemispheric electrodes, averaged between 300 and
407 2000 ms after S1, exceeded a fixed threshold of $\pm 80 \mu\text{V}$ (for any electrode pair), as
408 well as trials where difference values exceeded ± 4 standard deviations per individual
409 dataset (for at least two electrode pairs). The remaining EEG epochs entered *Fully*
410 *Automated Statistical Thresholding for EEG Artifact Rejection* (FASTER, Nolan,
411 Whelan, Reilly 2010) for the interpolation of noisy electrodes, and were subsequently
412 converted to current source densities (CSDs: iterations = 50, $m = 4$, $\lambda = 10^{-5}$;
413 Tenke and Kayser 2012). 93.4% of all epochs were retained for analysis after artifact
414 rejection (Experiment 1a: 92.9%, Experiment 1b: 93.2%, Experiment 2: 93.8%).
415 Statistical tests were based on correct and incorrect trials, since the exclusion of
416 incorrect trials did not change the pattern of results, but would have reduced the signal-
417 to-noise ratio of EEG data.

418

419 **Electrodes and EEG analyses** CSDs were separately averaged across three
420 adjacent electrode pairs contralateral and ipsilateral to the task-relevant side. Tactile
421 contralateral delay activity (tCDA component) was measured at lateral central scalp
422 regions (C3/4, FC3/4, CP3/4), and visual contralateral delay activity (CDA) was
423 measured at lateral occipital regions (PO7/8, PO3/4, O1/2). The electrode locations
424 used to quantify tCDA and CDA components were identical to those employed in
425 previous studies (Katus and Eimer 2016; Katus, Grubert, and Eimer 2017; Katus and
426 Eimer 2018a; 2018b). Separate CDA/tCDA components were computed for the delay
427 periods following the two sample sets (S1 and S2), based on averaged CSDs obtained
428 between 300 and 1000 ms following the onset of S1 or S2 (e.g., Katus and 2015; Vogel
429 and Machizawa 2004). Statistical tests of neural activity during these periods were
430 conducted on difference values of contra- minus ipsilateral CSDs. Error bars in graphs
431 indicate 95% confidence intervals (CIs) for the true population mean. Thus, error bars
432 that do not overlap with the zero axis ($y \neq 0$) indicate statistical significance of
433 tCDA/CDA components; error bars that do not overlap with chance level ($y \neq 50\%$)
434 indicate behavioral performance that is significantly above chance.

435 Spline-interpolated topographical voltage maps were computed as follows:
436 First, we averaged CSD amplitudes for the time windows of interest. These data were
437 collapsed across trials with left and right S1 targets by flipping electrode coordinates
438 over the midline for trials with left-side S1 targets. Trials were then averaged
439 separately for each experimental condition. To calculate contra-/ipsilateral difference
440 values, we used a copy of the data, and after flipping electrode coordinates over the
441 midline, we subtracted this inverted copy from the original data. This procedure
442 eliminates any non-lateralized activity, thereby revealing lateralized effects that reflect

443 amplitude differences between corresponding left- vs. right-hemisphere electrodes.
444 Note that the resulting full topographical maps are essentially equivalent to maps
445 where the inverse of the contra-ipsilateral amplitude difference measured over one
446 hemisphere is projected to the other hemisphere. As a result, these full topographic
447 maps show a symmetrical distribution of lateralized activity, which enhances the
448 visibility of tCDA and CDA components, and highlights the fact that the polarity of these
449 components can vary independently. In these maps, tCDA/CDA components evoked
450 by the S1 targets appear as negativity over the left hemisphere, and tCDA/CDA
451 polarity reversals during the period following S2 as a positivity over the left hemisphere
452 (i.e., a negativity over the right hemisphere).

453

454 **Bayes factor analysis** Conventional null-hypothesis significance tests can provide
455 evidence against the null hypothesis, but cannot confirm the null hypothesis for a
456 particular effect or interaction. We calculated Bayes factors using Bayesian t-tests
457 (Rouder et al. 2009) and the software Jasp (JASP team 2016) to formally decide
458 between the alternative and null hypotheses (i.e., presence vs. absence of a
459 modulation) for each main effect / interaction in our statistical designs. The Bayes
460 factor for the null-hypothesis (BF_{01}) corresponds to the inverse of the Bayes factor for
461 the alternative hypothesis (BF_{10}), and indexes the relative evidence in the data for the
462 absence rather than presence of a statistical difference. We always report the
463 numerically larger BF. Reliable evidence for either hypothesis is marked by a $BF > 3$
464 (Jeffreys 1961), suggesting that the empirical data are at least 3 times more likely
465 under this hypothesis as compared to the competing hypothesis.

466

467

468 **Results**

469 **Experiment 1a**

470 Figure 2 displays CSDs recorded over visual and somatosensory brain areas
471 contralateral and ipsilateral to task-relevant S1 items in Experiment 1a, where vision
472 and touch were the primary and secondary modality, respectively. The corresponding
473 contralateral-ipsilateral difference waves are shown in Figure 3a. As illustrated in the
474 left panels of Figure 2, the maintenance of visual sample stimuli in WM elicited visual
475 CDA components in all experimental conditions¹. As predicted, the CDA reversed
476 polarity during the delay period following S2 on shift trials but not on stay trials.
477 Importantly, this CDA polarity reversal was very similar in unimodal blocks and in
478 bimodal blocks where tactile stimuli from the S1 set had to be maintained concurrently;
479 see Figure 3a. A somatosensory tCDA component was elicited during the
480 maintenance of these stimuli in the S1 and S2 delay periods in bimodal blocks but was
481 absent in unimodal blocks. In the period following S2, tCDA components were
482 essentially unaffected by whether and attention shift was required in response to S2
483 in the visual modality; Figure 3a.

484

485 -----

486 insert Figure 2 about here

487 -----

¹ Unless explicitly stated otherwise, all tCDA/CDA components reported in this article were statistically significant, as confirmed by t-tests of contra/ipsi difference values against zero. The reliable presence of these components is shown in Figures 3 and 7, where statistically reliable modulations are indicated by error bars that do not overlap with the zero-axis (see Methods for further details).

488 **Primary modality (Vision, CDA components).** CSD values obtained during the
489 delay period following S2 were analyzed by separate ANOVAs with the factors *Task*
490 *type* (unimodal vs. bimodal) and *Trial type* (stay vs. shift). Because stay versus shift
491 trials only differed with respect to the side where visual S2 targets were presented,
492 these trials were collapsed for the analysis of CDAs during the S1-period. CDA
493 amplitudes were reduced in the bimodal task where both tactile and visual S1 targets
494 had to be maintained relative to the unimodal task where touch was irrelevant. These
495 bimodal costs for CDA amplitudes were present both during the S1-period (*Task type*:
496 $t(11) = 3.900$, $p = 0.003$, $BF_{10} = 18.689$) and during the S2-period (*Task type*: $F(1,11)$
497 $= 9.859$, $p = 0.009$, $BF_{10} = 6.217$). CDA components reversed polarity during the S2-
498 period on shift trials but not on stay trials (*Trial type*: $F(1,11) = 35.986$, $p = 10^{-4}$, BF_{10}
499 $= 317.813$). Importantly, the size of this CDA difference between stay and shift trials
500 was identical in unimodal and bimodal blocks (*Task type* x *Trial type*: $F(1,11) = 0.067$,
501 $p = 0.800$, $BF_{01} = 3.379$); see Figure 3, left side.

502 A follow-up ANOVA tested whether the reduction of CDA amplitudes in bimodal
503 as compared to unimodal blocks, which was already present in the S1-period, might
504 have obscured any interaction between *Task type* and *Trial type* in the S2-period. To
505 eliminate any effects associated with CDA amplitude differences during the first delay
506 period, we used the full S1-period as a new baseline, by subtracting CDA amplitudes
507 measured in the S1-period from those measured after S2. This subtraction eliminated
508 the *Task type* main effect ($F(1,11) = 0.070$, $p = 0.796$, $BF_{01} = 3.375$) and increased the
509 *Trial type* effect ($F(1,11) = 48.031$, $p < 10^{-4}$, $BF_{10} = 970.181$) for CDAs during the S2-
510 period. Critically, there was still no interaction between these two factors (*Task type* x
511 *Trial type*: $F(1,11) = 0.009$, $p = 0.926$, $BF_{01} = 3.466$). These results demonstrate that

512 the sustained maintenance of tactile information on one side in bimodal blocks had no
513 effect on the polarity shift of visual CDA components on switch versus stay trials.

514

515 **Secondary modality (Touch, tCDA component)** The tCDA was analyzed in the
516 same fashion as the CDA (see above). A reliable tCDA component was elicited during
517 the S1-period in the bimodal task ($t(11) = 5.590$, $p < 10^{-3}$, $BF_{10} = 189.203$), but not in
518 the unimodal task ($t(11) = 0.656$, $p = 0.526$, $BF_{01} = 2.894$; main effect of *Task type*:
519 $t(11) = 5.114$, $p < 10^{-3}$, $BF_{10} = 101.232$). This tCDA difference between the bimodal
520 and unimodal tasks persisted during the S2-period (*Task type*: $F(1,11) = 12.237$, $p =$
521 0.005 , $BF_{10} = 10.456$). There were no other significant effects in the S2-period (*Trial*
522 *type*: $F(1,11) = 1.816$, $p = 0.205$, $BF_{01} = 1.670$; *Trial type* x *Task type*: $F(1,11) = 0.336$,
523 $p = 0.574$, $BF_{01} = 3.012$). In bimodal blocks, tCDA amplitudes during the S2-period did
524 not significantly differ between visual stay and shift trials ($t(11) = 0.602$, $p = 0.560$,
525 $BF_{01} = 2.978$). This result did not change after subtracting an S1-period baseline from
526 tCDA amplitudes in the S2-period ($t(11) = 0.163$, $p = 0.874$, $BF_{01} = 3.440$), indicating
527 that attention shifts in the primary visual modality did not affect concurrent tactile WM
528 maintenance processes.

529

530 -----

531 insert Figure 3 about here

532 -----

533

534 **Behavioral data** Participants responded correctly in 85.1% of trials when memory was
535 tested for the primary modality (vision). The accuracy on trials in the bimodal WM task
536 where memory was tested for touch was 87.9%. Accuracy for the visual WM task was

537 reduced in bimodal relative to unimodal blocks (83.2% vs. 87.0% correct; *Task type*:
538 $F(1, 11) = 18.076$, $p = 0.001$, $BF_{10} = 30.861$); see Figure 4A. There were no other
539 significant effects or interactions for visual WM performance (*Trial type* \times *Task type*:
540 $F(1, 11) = 0.311$, $p = 0.588$, $BF_{01} = 3.044$; *Trial type*: $F(1, 11) = 0.991$, $p = 0.341$, BF_{01}
541 $= 2.299$). Accuracy for the tactile WM task in bimodal blocks was not significantly
542 reduced in visual shift as compared to stay trials (86.4% vs. 89.4% correct; *Trial type*:
543 $t(11) = 1.979$, $p = 0.073$, $BF_{10} = 1.242$).

544

545 -----

546 insert Figure 4 about here

547 -----

548

549 **Experiment 1b**

550 In Experiment 1b, touch was the primary and vision secondary modality. Tactile and
551 visual CDA components elicited by tactile and visual sample stimuli are shown in
552 Figure 5, and the corresponding difference waveforms are displayed in Figure 3B. The
553 pattern of CDA modulations observed for the primary and secondary modalities were
554 very similar to the results of Experiment 1a; see Figure 2. For the primary tactile WM
555 task, tCDA components reversed polarity in the S2-period on tactile shift trials, and
556 this was the case not only in unimodal but also in bimodal blocks. Visual sample stimuli
557 at S1 triggered CDA components in the bimodal task but not in the unimodal task when
558 they were irrelevant. Importantly, visual CDAs observed during the S2-period in
559 bimodal blocks did not change polarity on tactile shift trials.

560

561

562 -----

563 insert Figure 5 about here

564 -----

565

566 **Primary modality (Touch, tCDA components)** CSD values obtained during the
567 delay periods following S1 and S2 were analyzed with the same statistical tests as in
568 Experiment 1a. The amplitudes of tCDA components were reduced in bimodal as
569 compared to unimodal blocks during the S1-period (*Task type*: $t(15) = 2.801$, $p = 0.013$,
570 $BF_{10} = 4.293$), as was found for the visual CDA in Experiment 1a. However, this tCDA
571 amplitude difference between the two tasks was no longer present during the S2-
572 period (*Task type*: $F(1,15) = 0.006$, $p = 0.939$, $BF_{01} = 3.904$). As predicted, the tCDA
573 reversed its polarity during the S2-period on tactile shift trials but not on tactile stay
574 trials (*Trial type*: $F(1,15) = 54.076$, $p < 10^{-5}$, $BF_{10} > 10^3$). Critically, there was no *Task*
575 *type* \times *Trial type* interaction ($F(1,15) = 0.016$, $p = 0.900$, $BF_{01} = 3.887$), demonstrating
576 that this tCDA polarity reversal did not differ between the bimodal task where visual
577 S1 sample stimuli on one side had to be maintained throughout, and the unimodal task
578 where visual samples could be ignored; see Figures 3B and 5.

579 These results were confirmed in a control analysis, where the S1-period
580 baseline was subtracted from activity in the S2-period, as in Experiment 1a. There was
581 a main effect for *Trial type* ($F(1,15) = 60.670$, $p < 10^{-5}$, $BF_{10} > 10^4$), no significant effect
582 for *Task type* ($F(1,15) = 4.293$, $p = 0.056$, $BF_{10} = 1.379$), and importantly, no interaction
583 between both factors (*Trial type* \times *Task type*: $F(1,15) = 0.034$, $p = 0.856$, $BF_{01} = 3.856$).

584

585

586 **Secondary modality (Vision, CDA components)** During the S1-period, reliable CDA
587 components only emerged in the bimodal task ($t(15) = 6.133$, $p < 10^{-4}$, $BF_{10} > 10^3$), but
588 not in the unimodal task where visual sample stimuli were irrelevant ($t(15) = 1.395$, p
589 $= 0.183$, $BF_{01} = 1.730$), and this difference was significant (*Task type*: $t(15) = 6.098$, p
590 $< 10^{-4}$, $BF_{10} > 10^3$). This CDA difference between the two tasks remained present
591 during the S2-period (*Task type*: $F(1, 15) = 12.237$, $p = 0.005$, $BF_{10} = 10.456$). There
592 were no other significant effects for CDA amplitudes during the S2-period (*Trial type*:
593 $F(1, 15) = 1.816$, $p = 0.205$, $BF_{01} = 1.670$; *Trial type* \times *Task type*: $F(1, 15) = 0.336$, $p =$
594 0.574 , $BF_{01} = 3.012$). Importantly, CDA amplitudes measured in the bimodal task did
595 not differ between tactile stay versus shift trials ($t(15) = 0.647$, $p = 0.527$, $BF_{01} = 3.256$),
596 and this pattern did not change when an S1-period baseline was subtracted from the
597 CDA ($t(15) = 0.093$, $p = 0.927$, $BF_{01} = 3.900$).

598

599 **Behavioral data** Observers responded correctly in 90.3% of all trials in which memory
600 was tested for the primary modality (touch), and in 92.4% of bimodal trials where
601 memory was tested for vision; see Figure 4A. Tactile WM accuracy was reduced in
602 bimodal relative to unimodal blocks (87.2% vs. 90.3% correct; *Task type*: $F(1, 15) =$
603 8.219 , $p = 0.012$, $BF_{10} = 4.786$). Performance in response to tactile test stimuli was
604 worse in tactile shift versus stay trials (84.5% vs. 93.0% correct; *Trial type*: $F(1, 15) =$
605 18.030 , $p = 0.001$, $BF_{10} = 51.782$), demonstrating that participants found it more
606 difficult to retain the locations of tactile samples presented successively to different
607 hands. However, there was no *Task type* \times *Trial type* interaction ($F(1, 15) = 0.976$, $p =$
608 0.339 , $BF_{01} = 2.568$), indicating that performance costs on tactile shift trials were
609 equally present in unimodal and bimodal blocks, and were thus unrelated to the
610 additional requirement to maintain visual sample stimuli on one side. WM accuracy for

611 vision as secondary modality in the bimodal task did not differ between tactile shift and
612 stay trials (92.3% vs. 92.6%; *Trial type*: $t(15) = 0.235$, $p = 0.818$, $BF_{01} = 3.8201$).

613

614

615 **Experiment 2**

616 To further scrutinize the apparent independence of the space-based attentional control
617 of visual and tactile WM maintenance, Experiment 2 employed an orthogonal design
618 where the presence versus absence of shifts between the task-relevant tactile or visual
619 samples at S1 and S2 was manipulated independently for each modality. In addition,
620 the visual WM task was changed relative to Experiment 1. As was the case for the
621 tactile WM task, it now also involved the retention of spatial locations (see Figure 1C).
622 In Experiment 2, there were no unimodal blocks, and no distinction between primary
623 and secondary modalities. On all trials, bimodal visual/tactile sample sets were
624 presented at S1 and S2, and participants had to memorize task-relevant sample items
625 on one side for each sample set. The visual and tactile S1 targets were always located
626 on the same side, and this side remained constant within blocks. Visual and tactile S2
627 targets could appear on the same side or on the opposite side, and this was
628 manipulated independently, resulting in four trial types (vision & touch stay; vision &
629 touch shift; vision stay / touch shift; vision shift / touch stay).

630

631 -----

632 insert Figure 6 about here

633 -----

634

635 **Visual and somatosensory delay activity (CDA/tCDA)** Tactile and visual CDA
 636 components entered the same ANOVA, with *Component* (tCDA: CSD values at C3/4,
 637 FC3/4, CP3/4; CDA: CSD values at PO7/8, PO3/4, O1/2) included as a separate
 638 factor. Because the CDA and tCDA components index modality-specific WM
 639 maintenance processes (Katus and Eimer 2016), the difference between visual stay
 640 and shift trials should primarily affect the visual CDA during the S2-period (*Tracked*
 641 *Trial type*, TT: stay vs. shift), but not the somatosensory tCDA (*Untracked Trial type*,
 642 UT: stay vs. shift). Analogously, the difference between tactile stay and shift trials
 643 should primarily affect the tCDA, but not the CDA component during the S2-period.
 644 The data shown in Figure 6 and the corresponding difference waveforms shown in
 645 Figure 7 are in line with this prediction. CDA components changed polarity on visual
 646 shift trials, but were unaffected by whether the side of tactile target samples remained
 647 the same or shifted between S1 and S2. For tCDA components, there was a polarity
 648 reversal on tactile shift trials, but no difference between visual shift and stay trials.

649 In all four conditions of Experiment 2, and during both the S1- and S2-periods,
 650 reliable lateralized activity was present over visual and somatosensory cortex, as
 651 indicated by the error bars of contra-/ipsilateral difference values shown in Figure 7.
 652 Difference values obtained during the S1- and S2-periods were submitted to separate
 653 three-way ANOVAs with the factors TT (stay/shift), UT (stay/shift) and *Component*
 654 (tCDA/CDA). Since the locations of the tactile/visual S2 targets was unpredictable in
 655 all trials, there should be no significant effects for the factors TT / UT during the S1-
 656 period, and this was confirmed (TT: $F(1,15) = 0.005$, $p = 0.944$, $BF_{01} = 3.906$; UT:
 657 $F(1,15) = 0.027$, $p = 0.871$, $BF_{01} = 3.868$; *Component* x TT: $F(1,15) = 0.572$, $p = 0.461$,
 658 $BF_{01} = 3.048$; *Component* x UT: $F(1,15) = 0.075$, $p = 0.787$, $BF_{01} = 3.787$; TT x UT:
 659 $F(1,15) = 1.976$, $p = 0.180$, $BF_{01} = 1.710$; *Component* x TT x UT: $F(1,15) = 0.101$, $p =$

660 0.755, $BF_{01} = 3.743$). There was a main effect of *Component* during the S1-period
661 ($F(1,15) = 5.254$, $p = 0.037$, $BF_{10} = 1.911$), reflecting the known fact that CDA
662 amplitudes were generally larger than tCDA amplitudes (e.g., Katus and Eimer 2018a).

663 During the S2-period, a main effect of *Tracked Trial type* (TT: $F(1,15) = 42.116$,
664 $p < 10^{-5}$, $BF_{10} > 10^4$) was present, reflecting a polarity reversal of the visual CDA
665 component on visual shift trials, and of tactile CDA components on tactile shift trials;
666 see Figures 6 and 7. Critically, there was no main effects or interactions involving the
667 factor *Untracked Trial type* (UT: $F(1,15) = 0.058$, $p = 0.813$, $BF_{01} = 3.815$; TT x UT:
668 $F(1,15) = 0.230$, $p = 0.638$, $BF_{01} = 3.536$; *Component* x UT: $F(1,15) = 1.033$, $p = 0.326$,
669 $BF_{01} = 2.507$; *Component* x TT x UT: $F(1,15) = 0.119$, $p = 0.735$, $BF_{01} = 3.713$). This
670 demonstrates that the visual CDA was unaffected by the presence or absence of shifts
671 in touch, and that the tactile CDA was not sensitive to the difference between visual
672 stay versus switch trials. There was no significant main effect of *Component* in the S2-
673 period ($F(1,15) = 0.873$, $p = 0.365$, $BF_{01} = 2.681$), but there was an interaction between
674 *Component* and TT ($F(1,15) = 9.755$, $p = 0.007$, $BF_{10} = 7.370$). This interaction reflects
675 the fact that CDA amplitude differences between visual stay versus shift trials were
676 larger than the corresponding tCDA amplitude differences between tactile stay and
677 shift trials); note the different scales for tCDA/CDA components in Figure 7. Due to the
678 absence of any differential effects of TT or UT during the S1-period in Experiment 2
679 (see above), no additional control analyses with S1-period baselines were conducted
680 for CDA amplitudes following S2.

681 -----

682 insert Figure 7 about here

683 -----

684 **Behavioral data** Participants responded correctly in 78.5% of all trials. The
685 percentage of correct responses entered an ANOVA with the factors *Tested modality*
686 *Trial type* (TT: stay/shift), *Untested modality Trial type* (UT: stay/shift) and *Tested*
687 *modality* (vision or touch). Accuracy was higher when touch was tested than when
688 vision was tested (82.6% vs. 74.5%; *Tested modality*: $F(1,15) = 7.362$, $p = 0.016$, BF_{10}
689 $= 3.717$), reflecting the lower WM load for the tactile task (1 target item per sample
690 set) than for the visual task (2 targets per set). WM performance for the tested modality
691 tended to be worse on shift trials relative to stay trials, but this reduction was not
692 significant (TT: $F(1,15) = 3.778$, $p = 0.071$, $BF_{10} = 1.150$). Importantly, accuracy in the
693 tested modality was unaffected by the presence versus absence of a location shift for
694 relevant sample items in the untested modality (UT: $F(1,15) = 0.091$, $p = 0.767$, BF_{01}
695 $= 3.760$). There was also no interaction between stay/shift trials in the tested and
696 untested modalities (TT x UT: $F(1,15) = 0.196$, $p = 0.665$, $BF_{01} = 3.589$). Further effects
697 were non-significant (TT x UT x *Tested modality*: $F(1,15) = 0.042$, $p = 0.841$, $BF_{01} =$
698 3.842 ; TT x *Tested modality*: $F(1,15) = 2.702$, $p = 0.121$, $BF_{01} = 1.292$; UT x *Tested*
699 *modality*: $F(1,15) = 1.308$, $p = 0.271$, $BF_{01} = 2.237$).

700 To test whether the presence versus absence of attention shifts in the tested or
701 untested modality during the S2-period selectively affected the retention of S2 sample
702 stimuli that had to be encoded in this period, additional analyses of WM accuracy were
703 conducted only for trials where memory was tested for S2 stimuli, separately for hit
704 rates (from match trials) and correct rejection rates (from mismatch trials). These
705 analyses involved the factors *Tested modality* (touch or vision), *Tested modality Trial*
706 *type* (TT: stay or shift) and *Untested modality Trial type* (UT: stay or shift). For hit rates,
707 accuracy was again higher for tactile as compared to visual memory probes ($F(1, 15)$
708 $= 11.657$, $p = 0.004$, $BF_{10} = 12.142$). There were no significant effects or interactions

709 involving TT or UT (all p s > 0.05), indicating that attention shifts in either modality had
710 no impact on memory for S2 items. For correct rejection rates, no significant effects
711 were found (p s > 0.05).

712

713

714 **Discussion**

715 To examine the flexibility of space-based attentional control mechanisms in
716 multimodal WM, we employed sequential loading procedures in bimodal visual/tactile
717 WM tasks, and measured visual and tactile CDA components as ERP markers of the
718 attentional activation of WM representations in modality-specific visual and
719 somatosensory brain regions. On each trial, two memory sample sets (S1/S2) were
720 presented sequentially, and the critical manipulation was whether the S1 and S2
721 targets in a given modality were located on the same side or on opposite sides (stay
722 vs. shift trials).

723 Experiment 1 included unimodal baseline conditions where only primary-
724 modality stimuli (vision in Exp.1a, touch in Exp.1b) were task-relevant and S1 sample
725 sets in the other modality could be ignored. In these unimodal WM tasks, visual and
726 tactile CDA components were elicited contralateral to S1 targets in the S1-period and
727 then reversed polarity during the S2-period on shift trials. This confirms previous
728 observations from unimodal tactile and visual sequential loading experiments (Katus
729 and Eimer 2015; Berggren and Eimer 2016), and indicates that spatial attention was
730 reallocated to the location of S2 targets during the second delay period. In these two
731 unimodal baseline tasks, there were no reliable CDA components over visual areas in
732 blocks where visual sample stimuli had be ignored, and no significant tCDA

733 components over somatosensory areas in blocks where tactile samples were irrelevant.
734 These observations show that the presence of these components was determined by
735 the task-relevance of the corresponding sensory modality. This also demonstrates the
736 feasibility of our CDA/tCDA co-registration methods using CSDs in preventing any
737 carryover of lateralized ERP effects from visual to somatosensory areas, or vice versa
738 (see also Katus and Eimer, 2016; Katus, Grubert, Eimer 2017; Katus and Eimer,
739 2018a; 2018b; for additional evidence for the separability of CDA and tCDA
740 components in bimodal visual/tactile WM tasks).

741 The critical question addressed in Experiment 1 was whether there would be
742 any spatial synergies between space-based attentional control processes in bimodal
743 visual/tactile blocks where sample stimuli from both modalities had to be maintained.
744 In Experiment 1a, vision was the primary modality. There were visual stay and shift
745 trials, and observers also had to maintain tactile S1 targets throughout the delay
746 periods following S1 and S2. The visual CDA initially emerged over the hemisphere
747 contralateral to visual S1 targets, and reversed polarity on shift trials when visual S2
748 targets were presented on the opposite side. Crucially, this CDA polarity reversal was
749 identical in unimodal and bimodal blocks, and Bayesian tests confirmed the absence
750 of Trial Type x Block Type interactions in the S2-period. Thus, having to maintain a
751 sustained attentional focus on one side in tactile WM had no effect on the execution
752 of spatial attention shifts in visual WM towards S2 targets on shift trials. Exactly the
753 same pattern of CDA results was observed in Experiment 1b, where the roles of vision
754 and touch as primary and secondary modalities were reversed. Here, tactile CDA
755 components reversed polarity on shift trials, and this polarity reversal was identical in
756 unimodal and visual blocks. In addition, and importantly, having to re-allocate
757 attention to the opposite side versus maintaining attention on the same side in the

758 primary modality had no impact on the polarity and amplitudes of CDA components
759 for the secondary modality (touch in Exp 1a, vision in Exp 1b). This demonstrates that
760 the constant focus of spatial attention during the maintenance of WM representations
761 in the secondary modality remained unaffected by the presence versus absence of
762 attention shifts during the S2-period in the primary WM task.

763 In line with this apparent independence of space-based attentional control
764 mechanisms in visual and tactile WM, there were also no differences in WM
765 performance between bimodal shift and stay trials in Experiment 1. In particular,
766 accuracy on trials where WM for the secondary modality was tested was unaffected
767 by whether primary modality S1 and S2 targets were presented on the same or on
768 opposite sides. In other words, the maintenance of tactile or visual S1 samples was
769 not impaired when the attentional focus in the other modality had to be re-allocated to
770 the opposite side during the S2-period.

771 There was however a general bimodal cost for WM performance in Experiment
772 1. Accuracy for the WM task in the primary modality was higher in unimodal baseline
773 blocks relative to bimodal blocks, and this was the case both for vision in Exp.1a and
774 for touch in Exp.1b. These bimodal performance costs are in line with observations
775 from previous behavioral studies (e.g., Fougne and Marois 2011; Sauls and Cowan
776 2007), and they were accompanied by corresponding CDA differences between
777 unimodal and bimodal blocks. Visual and tactile CDA/tCDA amplitudes for the primary
778 tasks in Experiments 1a and 1b were smaller in bimodal blocks where secondary
779 modality sample items had to be maintained concurrently relative to unimodal blocks
780 where these items could be ignored (Task Type main effect). These findings are
781 consistent with a previous EEG experiment (Katus and Eimer 2018b) where CDA
782 amplitudes elicited during visual WM maintenance were generally smaller when this

783 task was performed concurrently with a tactile WM task, relative to a single-task
784 baseline condition. This CDA attenuation in the bimodal task was interpreted as a
785 result of the increased demands on central executive dual-task coordination
786 mechanisms, and thus as a limitation in the concurrent top-down control of multiple
787 WM maintenance processes in different modalities. Importantly, dual-tasking
788 attenuated visual CDA amplitudes by the same amount regardless of WM load in the
789 visual task, and visual load had no impact on tactile CDA amplitudes elicited during
790 the maintenance of tactile items in the bimodal task. These observations suggest that
791 these bimodal costs are unrelated to the capacity of sensory storage mechanisms (see
792 Katus and Eimer 2018b, for further discussion). To eliminate amplitude differences
793 between bimodal and unimodal task conditions during the S1-period, we ran additional
794 analyses of tCDA/CDA components elicited in the S2-period after subtracting out
795 tCDA/CDA amplitudes in the S1-period. This new baseline confirmed the absence of
796 any Task Type x Trial Type interactions in Experiments 1a and 1b, as indicated by
797 Bayesian analyses for both experiments. This result further underlines the
798 independence of modality-specificity attentional control processes in visual and tactile
799 WM, and demonstrates that this independence was unrelated to the dual-task
800 coordination costs that accounted for reduced tCDA/CDA amplitudes in bimodal
801 blocks during the S1-period.

802 In Experiment 1, attention shifts in the primary modality that took place during
803 the S1-period had no impact on the stable focus of attention within the secondary
804 modality that was already established during the S1-period. In Experiment 2, the
805 necessity to shift attention between S1 and S2 or to maintain an attentional focus on
806 the same side was orthogonally manipulated for visual and tactile WM, resulting in
807 trials requiring attention shifts in one modality, neither modality, or in both modalities

808 simultaneously. In contrast to Experiment 1, where participants memorized colors for
809 the visual task and locations for the tactile tasks, memory for spatial locations was
810 required for both tasks in Experiment 2. This change was introduced to maximize the
811 representational overlap between both modalities (see Tamber-Rosenau and Marois
812 2016, Exp. 8 in Fougny et al. 2015), and to test whether the independent attentional
813 control of visual and tactile WM found in Experiment 1 was linked to the fact that
814 different types of information (spatial vs. featural) had to be maintained in different
815 modalities (cf., Zimmer 2008). As in Experiment 1, visual CDA and CDA components
816 initially emerged contralateral to the S1 targets. During the S2-period, the polarity of
817 these CDA components was determined exclusively by the location of S2 target
818 sample items in the corresponding modality, and was entirely unaffected by whether
819 targets in the other untracked modality required a shift of spatial attention or not; see
820 Figure 6. The polarity of the visual and tactile CDAs reversed on visual or tactile shift
821 trials but not on visual or tactile stay trials, respectively (TT: Tracked Trial type main
822 effect; see topographical maps in Figure 7). Crucially, whether an attention shift was
823 or was not required within one modality during the S2-period had no impact on the
824 amplitudes of CDA components associated with the other modality (UT: Untracked
825 Trial type main effect). There was also no evidence for any interactions between these
826 two factors.

827 The behavioral results of Experiment 2 also demonstrated that WM
828 maintenance in vision and touch was not affected by the spatial relationship between
829 S1 and S2 targets in the other modality. WM accuracy for the modality that was tested
830 did not differ between trials with versus without a location shift of S1 and S2 targets in
831 the other untested modality. The reliability of all critical null effects for CDA/tCDA
832 amplitudes and WM performance was confirmed with Bayesian tests. Overall, these

833 results of Experiment 2 provide additional clear evidence for the independence of
834 space-based attentional control mechanisms in visual and tactile WM.

835 What do the observations of the present study imply for the architecture of
836 multimodal WM and its top-down control? The dynamic shifts of spatial attention
837 between WM representations and hemispheres that were observed in this and
838 previous sequential loading studies, as well as in experiments on multiple object
839 tracking (Drew et al. 2014a) could reflect the flexible updating of location pointers,
840 which control the activation profile of WM representations in modality-specific visual
841 or tactile spatial maps. The existence of such location pointers was initially proposed
842 as a mechanism for visual stability during saccadic eye movements (Cavanagh et al.
843 2010) and for the online tracking of visual objects (Oksama and Hyona 2008). The
844 Visual Indexing Theory (Pylyshyn 1989) proposes that objects are tracked via their
845 locations using spatial indices that convey no featural information about object-identity.
846 Similar pointer mechanisms could also be employed during the space-based
847 attentional control of WM maintenance. This hypothesis is compatible with accounts
848 proposing a map-based organization of WM (Franconeri, Alvarez, Cavanagh 2013),
849 where information is stored as hierarchical feature bundles (Brady, Konkle, Alvarez
850 2011) in distributed two-dimensional content maps. Objects in different sensory
851 modalities are stored in feature maps in modality-specific sensory areas, as suggested
852 by the sensory recruitment hypothesis of WM (Jonides, Lacey, Nee 2005). Because
853 maps in higher-level attentional control areas, such as prefrontal cortex, lack sensitivity
854 to low-level properties of stimuli (Serences 2016; Thompson and Bichot 2005), they
855 may instead provide the spatial pointer mechanisms that are necessary to select
856 particular items in WM in a top-down fashion. Such spatial indexing mechanisms for
857 individual memorized objects are particularly important if features of these objects

858 were represented in distributed modality-specific cortical maps. In this context, the
859 emergence of visual and tactile CDA component observed in the present study could
860 reflect the activation of WM representations in visual and tactile maps that is triggered
861 by top-down input from spatial pointers, and the polarity reversal of these components
862 on shift trials, the result of spatial updating processes within the location pointer
863 system. Our results suggest that spatial indexing occurs in parallel and independently
864 for objects stored in visual and tactile maps, allowing for strictly modality-specific
865 dynamic changes in the allocation of attention during WM maintenance.

866

867 **Conclusion:** Top-down control processes regulate the activation of representations
868 in sensory WM stores, and these processes operate in a dynamic and spatially
869 selective fashion. The maintenance of visual and tactile items is mediated by spatial
870 pointer mechanisms that specify the location of these items once they have been
871 encoded into WM. The independence of attention shifts within visual and tactile WM
872 indicates that the spatial indexing of somatotopic and retinotopic information is
873 mediated by parallel modality-specific processes that operate in distributed cortical
874 maps.

875

876

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878

879

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1002 **Figure legends**

1003 **Figure 1: Task design** (A) In Experiment 1a, vision was the primary modality and
1004 touch was the secondary modality. Each visual sample set contained circles and
1005 squares on opposite sides. On stay trials (50%), the circles and squares in S2 were
1006 presented on the same side as in S1. On shift trials (50%), the shapes swapped their
1007 locations across S1 and S2. Participants memorized the colors of all target shapes
1008 (circles or squares, counterbalanced) in S1 and S2. In bimodal blocks, participants
1009 also memorized the locations of the tactile S1 stimuli on the same side as the visual
1010 S1 targets, as memory was unpredictably tested for vision or touch (50%
1011 match/mismatch). In unimodal blocks, memory was always tested for vision, and
1012 tactile stimuli could be ignored. (B) In Experiment 1b, touch was the primary modality.
1013 Tactile targets were defined by stimulus waveform (pulsed or continuous,
1014 counterbalanced). Participants memorized the locations of the S1 and S2 targets,
1015 either on the same hand or on different hands (50% stay/shift). In bimodal blocks,
1016 participants also memorized the colors of the visual S1 stimuli on the same side as the
1017 tactile S1 target, and memory was unpredictably tested for touch or vision. In unimodal
1018 blocks, only touch was tested. (C) In Experiment 2, bimodal S1 and S2 sample
1019 stimulus sets were followed unpredictably by a tactile or visual test set. Participants
1020 memorized the locations of visual targets defined by color (green/red) and tactile
1021 targets defined by waveform (pulsed/continuous). Visual and tactile S1 targets were
1022 always located on the same side, and the location of the S2 targets (same/different
1023 side) was orthogonally manipulated for touch and vision (50% stay or shift trials for
1024 each modality).

1025

1026 **Figure 2. CDA components in Experiment 1a** CSDs recorded in unimodal and
1027 bimodal blocks contralateral and ipsilateral to the S1-targets (thick vs. thin lines) over
1028 brain regions associated with the primary task (vision: CDA, left panels) and secondary
1029 task (touch: tCDA, right panels) are shown separately for visual stay and shift trials.
1030 Visual CDA components changed polarity on shift trials in the period after S2, in both
1031 unimodal and bimodal blocks. Tactile CDA components were absent in unimodal
1032 blocks where touch was task-irrelevant but present in bimodal blocks. The tCDA
1033 remained present during the period following S2, and did not differ between visual stay
1034 and shift trials.

1035

1036 **Figure 3. Contra-/ ipsilateral difference waves from Experiment 1a and 1b (left**
1037 **vs. right column)** Visual and tactile CDA components associated with the primary
1038 modality (vision in Exp. 1a, touch in Exp. 1b) are shown in the two top panels for
1039 primary-modality stay and shift trials, separately for the unimodal and bimodal tasks.
1040 The panel below shows tactile and visual CDA components for the secondary modality
1041 in the bimodal task, separately for stay and shift trials in the primary modality. Note the
1042 different scales for the tCDA and CDA. Error bars/colored shadings indicate the
1043 confidence intervals for the true population mean. The topographical maps in the
1044 bottom panel display the distribution of lateralized delay activity during the S1- and S2-
1045 periods (top and bottom rows) for stay and shift trials in the unimodal and bimodal WM
1046 tasks of Experiments 1a and 1b.

1047

1048 **Figure 4. Behavioral performance in Experiments 1a, 1b and 2 (A)** WM accuracy
1049 in Experiment 1a (top) and Experiment 1b (bottom), where vision or touch were the
1050 primary modalities, respectively. Visual and tactile WM performance on stay and shift

1051 trials is shown separately for the primary modality (in the unimodal and bimodal tasks)
1052 and for the secondary modality (in the bimodal task). (B) WM accuracy in Experiment
1053 2, for trials where memory was tested for the visual task (top) or tactile task (bottom),
1054 shown separately for stay and shift trials in the tested and untested modality.

1055

1056 **Figure 5. CSD amplitudes from Experiment 1b** CSDs measured over
1057 somatosensory and visual areas contralateral and ipsilateral to task-relevant side of
1058 S1 sample sets in the unimodal and bimodal tasks. The tCDA reversed polarity during
1059 the S2-period on tactile shift trials in both tasks. There was no corresponding polarity
1060 change of visual CDA components in the bimodal task on tactile shift trials.

1061

1062 **Figure 6. CSD amplitudes from Experiment 2** Visual and somatosensory CDA
1063 components recorded contra- and ipsilateral to task-relevant sample items in S1,
1064 shown separately for trials with a S1-S2 target location shift in neither modality, in
1065 vision only, touch only, or in both modalities. Visual and tactile CDA components
1066 reversed polarity in the S2-period on visual and tactile shift trials, respectively, but
1067 were unaffected by shifts in the other untracked modality. Note the different scales for
1068 visual and tactile CSDs.

1069

1070 **Figure 7. Contra-ipsilateral difference waves from Experiment 2.** The left panel
1071 shows visual CDA components elicited on visual stay and shift trials, separately for
1072 trials where the position of tactile targets in S1 and S2 remained the same or changed
1073 (Touch Stay versus Touch Shift, in green vs. red). The right panel shows the
1074 corresponding tactile tCDA components for tactile stay and shift trials (Vision Stay
1075 versus Vision Shift, in green vs. red). The line graphs show mean tCDA/CDA

1076 amplitudes in the S1 and S2 periods of all four trial conditions. Error bars/colored
1077 shadings indicate confidence intervals; note the different scales for the tCDA and CDA.
1078 Topographical maps show the distribution of lateralized delay activity during the S1-
1079 and S2-periods (top and bottom panels) for the four trial types.

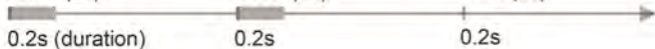
Event and timing (SOA)

Set 1 (0s)

Set 2 (1s)

Response period 1.8s

Test (2s)



(A) Experiment 1a. Primary modality: Vision

Vision + Touch



Vision only



Shift trial
Circles and squares
swap sides

Vision or Touch



(B) Experiment 1b. Primary modality: Touch

Vision + Touch



Pulsed Continuous

Touch only

Shift trial Pulsed
and continuous
waveforms swap
sides



Vision or Touch



(C) Experiment 2

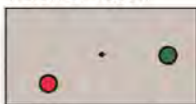
Vision + Touch

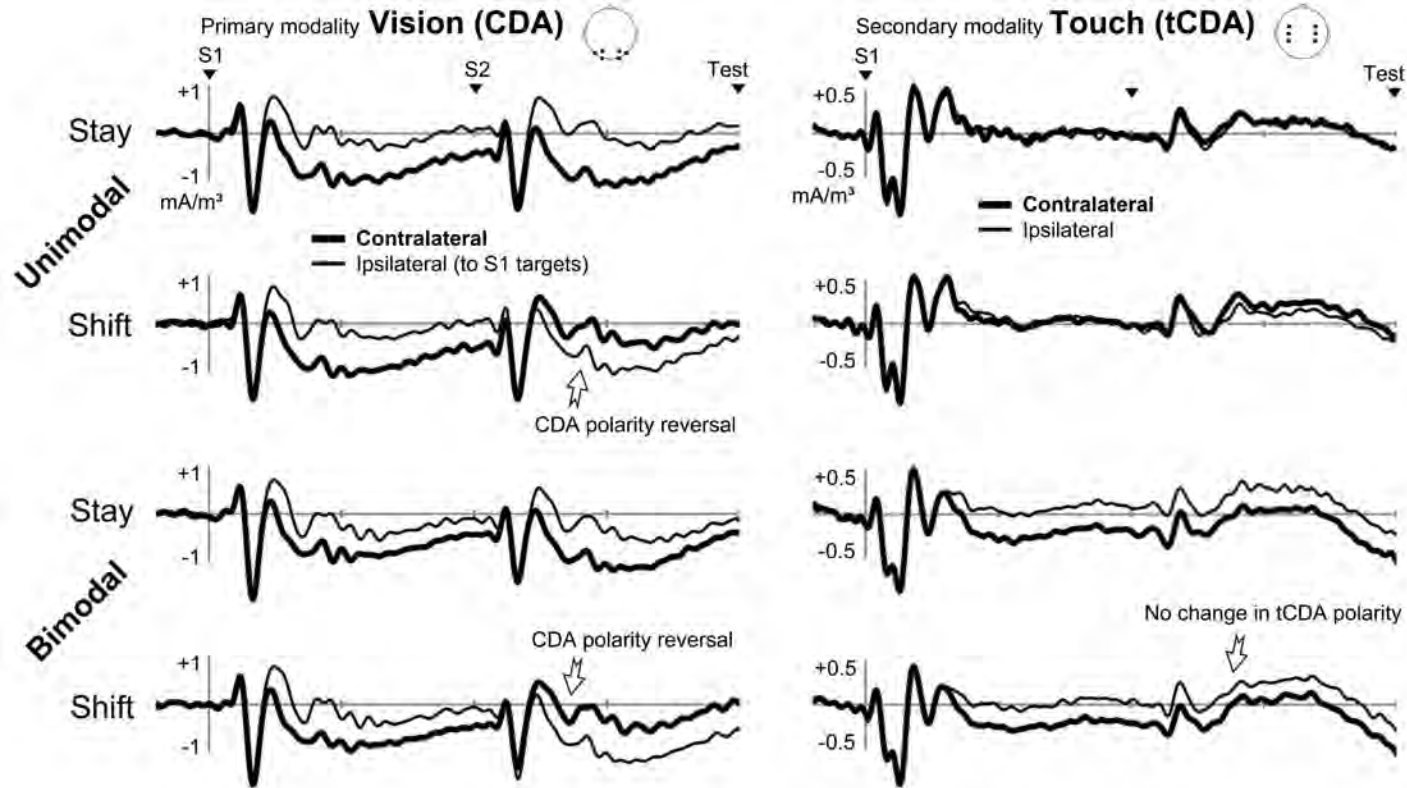


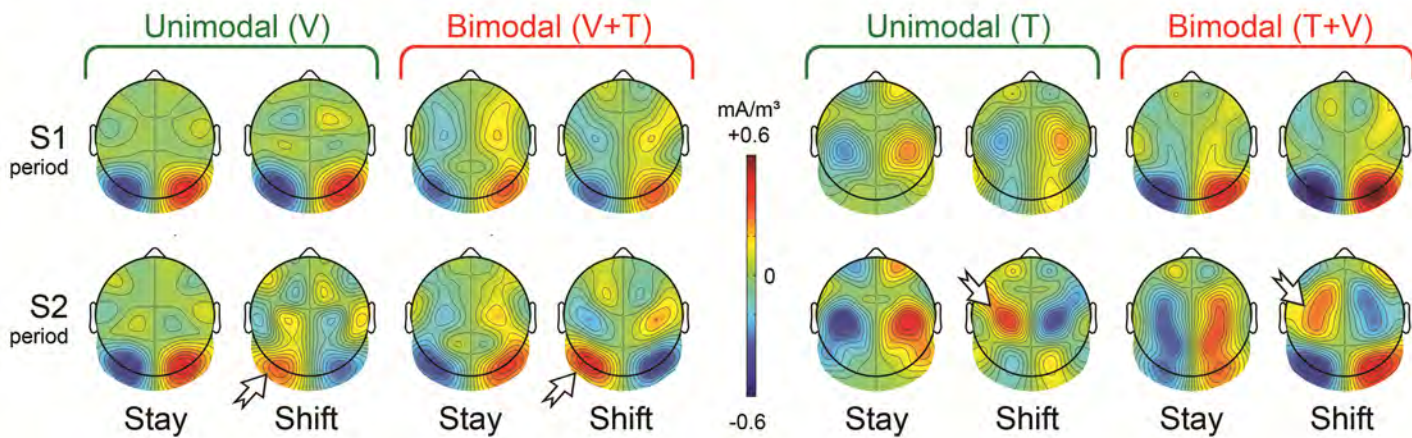
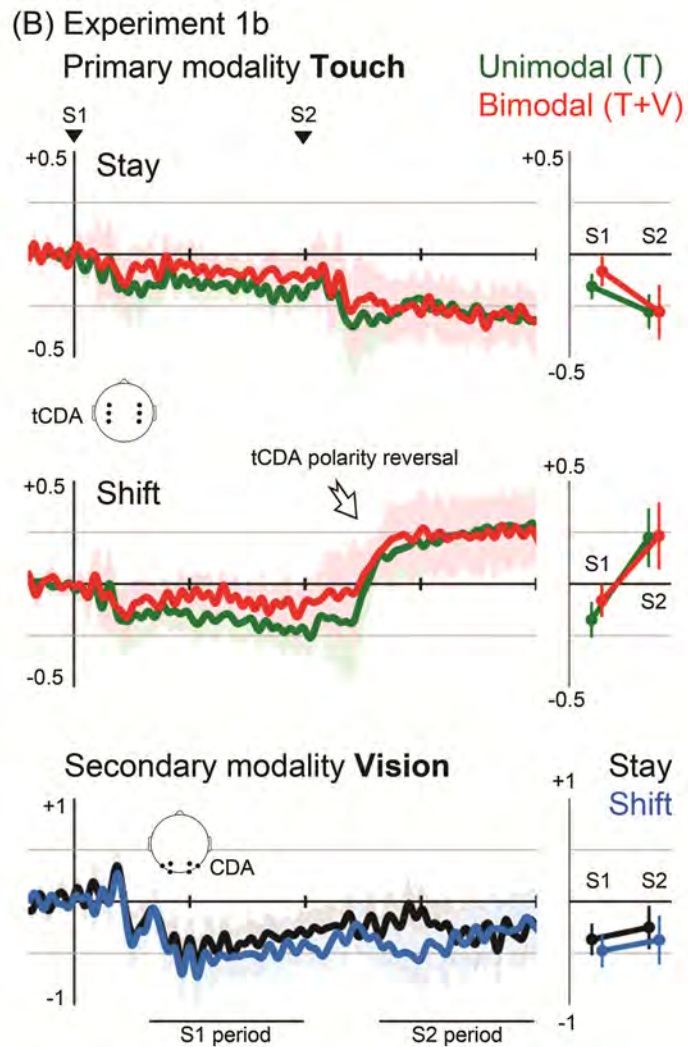
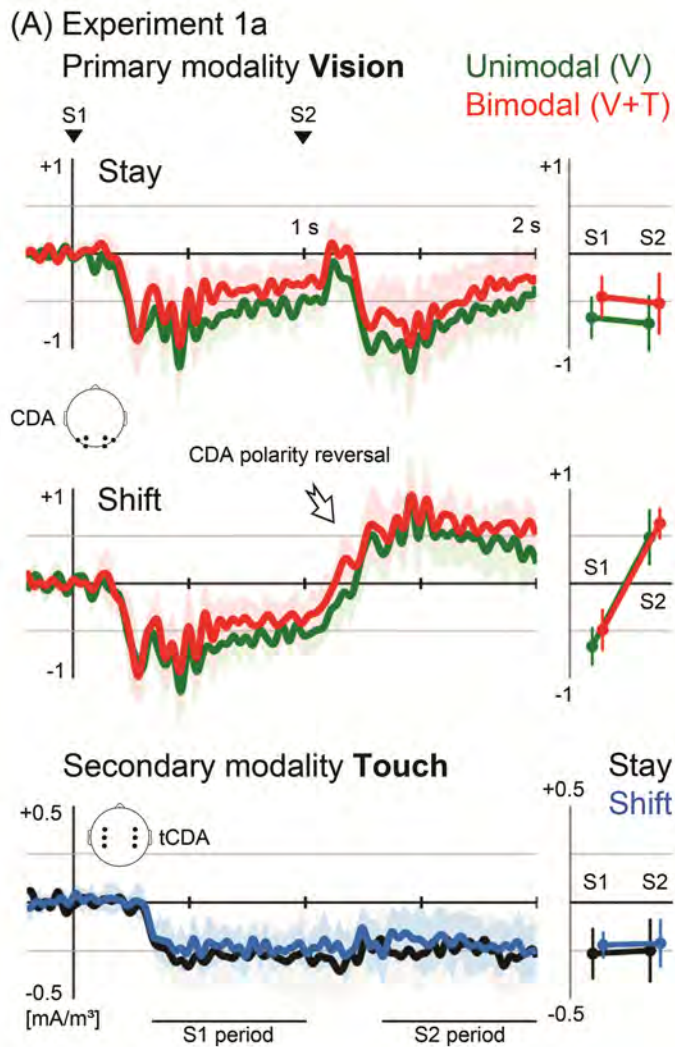
Vision + Touch



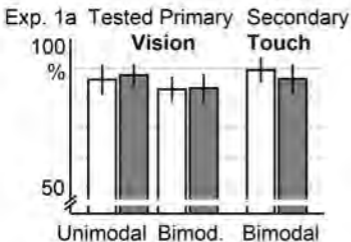
Vision or Touch



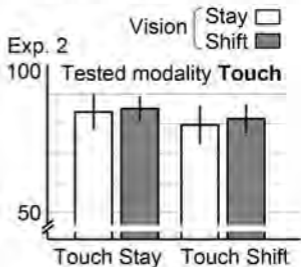
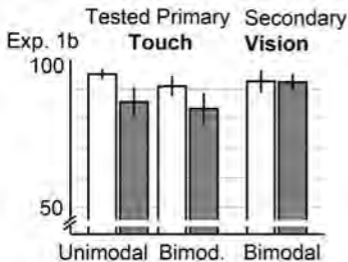
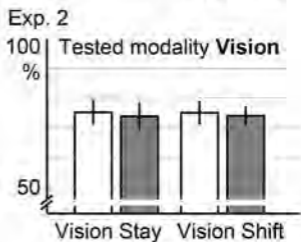


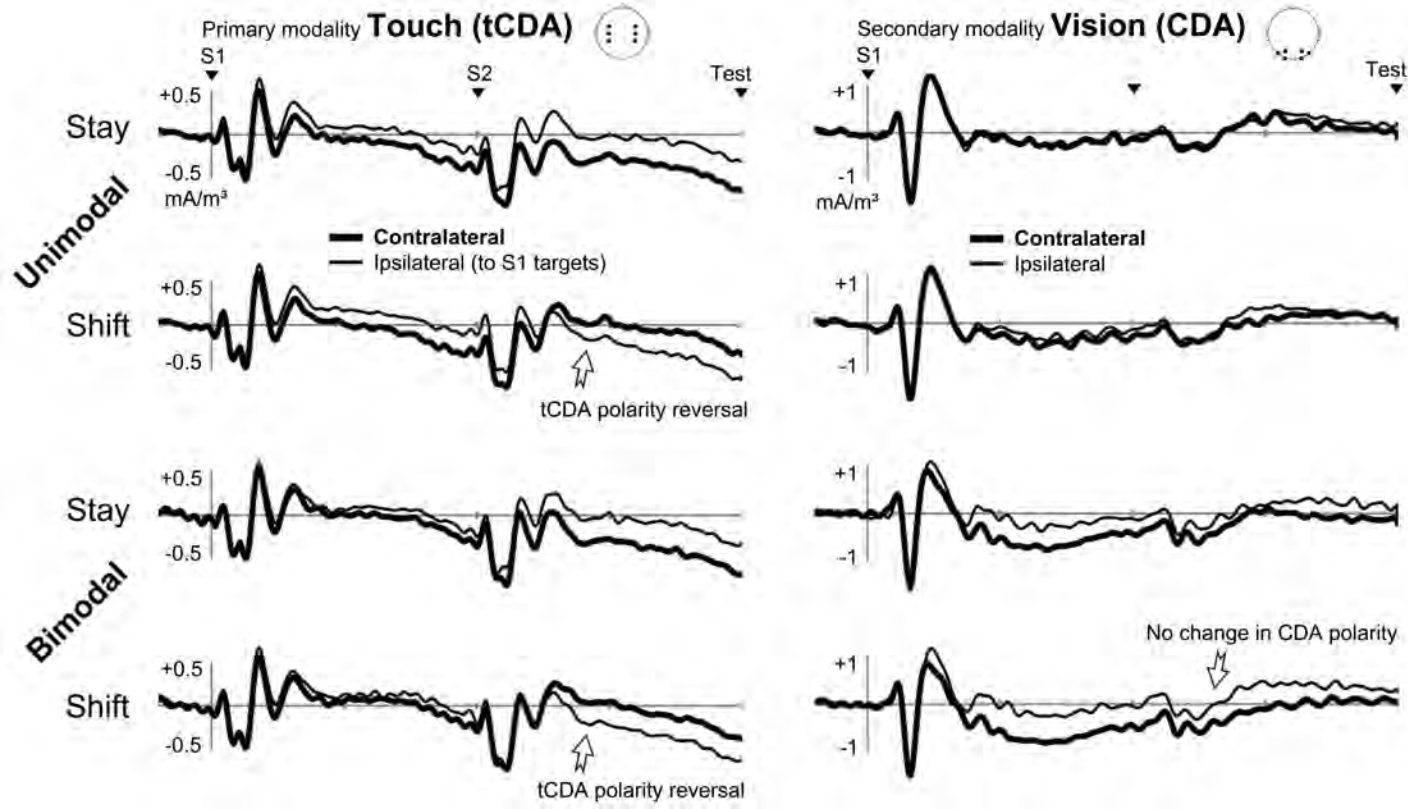


(A) Primary modality (Stay Shift)

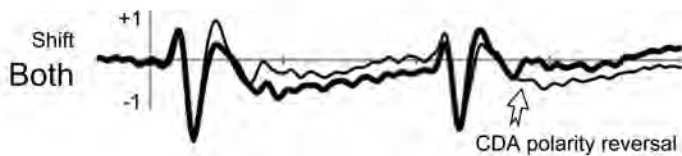
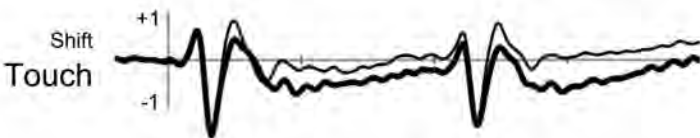
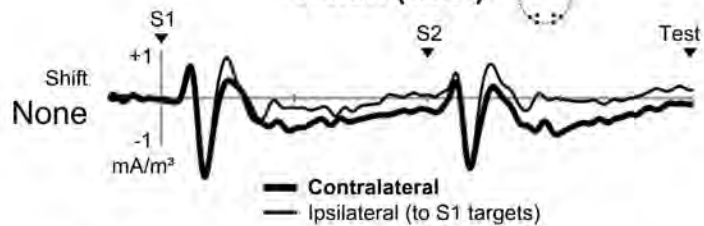


(B) Touch (Stay Shift)





Vision (CDA)



Touch (tCDA)

